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H. FOSTER BAIN, DIRECTOR

BITUMINOUS COAL AS GENERATOR FUEL FOR LARGE WATER-GAS SETS WITH WASTE-HEAT BOILERS

BY

WM. A. DUNKLEY

This paper represents work done under a cooperative agreement between the Bureau of Mines, Department of the Interior, the State Geological Survey Division of the State of Illinois, and the Engineering Experiment Station of the University of Illinois

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USE OF BITUMINOUS COAL AS GENERATOR FUEL FOR LARGE WATER-GAS SETS WITH WASTE-HEAT BOILERS

By Wm. A. Dunkley

INTRODUCTION

Under certain conditions in the fuel market the prices of coke or anthracite—the commonly used water-gas fuels—differ considerably from those of bituminous coal. Such differences were marked during the World War especially in the Middle West, and stimulated the study of methods of using bituminous coal for making water gas. Trouble was experienced during early attempts to use bituminous coal for this purpose. Mechanical difficulties caused some annoyance, but low production capacities and poor fuel efficiencies were even more discouraging.

After extensive experiments, operating methods were gradually improved, difficulties were almost entirely overcome, and fuel consumption per unit of gas production was so reduced, especially in the smaller water-gas sets, as to place bituminous coal almost on a par with low-volatile fuels, even at the same price per ton. Results have not been so promising for the larger sizes of water-gas sets—that is, those having generators 8 feet 6 inches or more in diameter—in which the tendencies hindering good efficiencies seem to be emphasized. In the water-gas sets of 11.0-foot generator diameter—the largest size commonly installed—these unfavorable tendencies are especially marked. Much study has been given to the use of bituminous coal in a battery of sets of this size in the plant of the Coal Products Manufacturing Co. at Joliet, Ill. The water-gas installation at this plant is new and is equipped with refinements found in a few other plants. It has been possible therefore to study the use of bituminous generator fuel under especially favorable conditions for about two years.

Although it can not be said that the difficulties of operation peculiar to the use of bituminous fuel in large sets have been entirely overcome at Joliet, the experiences have been instructive. This paper summarizes the tests up to January 1, 1923, shows the practical efficiencies obtained, and discusses economic phases of the

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process, in order that operators who contemplate using bituminous generator fuel may have some data upon which to base calculations when they try to estimate whether the use of such fuel would be economically feasible.

When this paper was written, fuel-market conditions were not as favorable to bituminous fuel as formerly. Nevertheless bituminous coal is still used in several plants, and since under certain conditions it can be used with noticeable saving in operating costs the subject is important to gas manufacturers. The use of this fuel also gives a water-gas plant increased flexibility under varying conditions of fuel supply.

A fact worthy of note is that the low-sulphur coals of Illinois and Indiana, which are not regarded as first-grade coals for coal-gas and coke manufacture, give results in the water-gas machine nearly as good as those obtained from eastern high-volatile coals. Hence, the more these Middle Western coals can take the place of coke from eastern coals, the more coke is saved for use in industries where bituminous coal can not be employed to advantage; moreover, transportation of coal from eastern fields is avoided.

ACKNOWLEDGMENTS

Most of the work for this paper was done in the plant of the Coal Products Manufacturing Co. at Joliet, Ill. Thanks are due Messrs. W. M. Willett, C. C. Boardman, W. J. Murdock, E. E. Lundgren, and W. R. Bigelow, officials of the company, for their hearty cooperation at all times. Other company employees assisted efficiently and helpfully in the various tests and operations whose results are reported here.

PREVIOUS STUDIES OF BITUMINOUS COAL AS GENERATOR FUEL

Developing the use of bituminous coals as generator fuel in water-gas production has been the work of many individuals. Doubtless many unreported experiments have been made with results not encouraging enough to warrant continued operation. Among the most successful attempts are those that have been made in the Middle West. Some of the pioneer plants that use the process are those at East St. Louis, Ill., and Beloit, Wis. Some of the plants of the Illinois Traction System also used coal intermittently for several years, even before the fuel stringency of 1917 and 1918. Fuel Administration measures at that time greatly accelerated the development of the process. Gas companies in the Middle West found it difficult or impossible to obtain enough coke to operate their water-gas plants and anthracite was unobtainable; many of them faced the alternatives of using raw coal or of shutting down. They

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recognized that intensive study of the use of coal was needed by men who could devote time to the technical aspects of the process without being obliged to direct their attention almost exclusively to the problems of obtaining fuel and labor and maintaining equipment, as most operating engineers and superintendents of plants were obliged to do.

TESTS AT STREATOR, ILL.

Early in 1918 the agencies of the cooperative mining agreement at the University of Illinois undertook the study with the cooperation of the gas industry. The Public Service Co. of Northern Illinois offered the use of the small water-gas plant at Streator, Ill., for test purposes. During an investigation which lasted several months, W. W. Odell, of the Bureau of Mines, and the writer of this paper, who was then with the Illinois State Geological Survey, studied a number of Illinois coals as water-gas fuel in the Streator plant under service conditions. The results of this investigation were reported in Cooperative Mining Investigations Bulletin 24 of the Illinois State Geological Survey.

The work at Streator demonstrated that in small water-gas sets not over 6 feet in external diameter, running only a few hours a day, the coals of southern Illinois can be used with success. By use of the right operating cycle and charging interval and proper weight of coal charged, and by adoption of the so-called "blow-run" cycle, in which a part of the richest blast gas is saved, it was possible to avoid almost entirely excessive production of smoke, caking of the generator fire, sticking of gas valves through pitch formation, and overheating of the oil-fixing chambers—all of which had characterized former operation with bituminous coals. A production capacity approximately 75 to 80 per cent of the nominal rated capacity of the apparatus could also be obtained even with the low blast pressure available—the rated capacity being based upon the use of good coke and a high blast pressure. In fact the production rate with coal was higher than could be obtained in the same sets with the coke and the blast pressure available under the usual operating conditions.

TESTS AT BELOIT, WIS.

While the Streator tests were going on, other operators were trying coal as generator fuel. Many of these experiments, although quite successful, were not reported in the technical press. R. G. Krumrey[1] has discussed the results obtained in the 6-foot water-gas sets he was operating at Beloit, Wis. His results were much like

[1] Krumrey, R. G., Experiments with bituminous coal in the manufacture of water gas: Am. Gas Eng. Jour., vol. 110, Apr. 5, 1919, p. 291

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those obtained at Streator. Krumrey was also able to present a cost summary, covering an operating period of one year, in which he showed that in his plant with coal as generator fuel certain items of production cost, including boiler fuel, maintenance, and labor, increased 2.48 cents per 1,00 cubic feet of gas made. Offsetting this increase was a saving, with coal fuel, of 11.62 cents per 1,000 cubic feet of gas through the lower cost of the coal, as compared with coke, and the smaller quantity of oil necessary to maintain the required B. t. u. standard.

TESTS AT DAVENPORT, IOWA

In 1920, W. W. Odell, of the Bureau of Mines, carefully studied the use of coal and mixtures of coal and coke in the 8-foot 6-inch sets of the United Light & Railways Co. at Davenport, Iowa. These results were reported in Technical Paper 284 of the Bureau of Mines. Odell found that in water-gas generators charges of mixed fuel containing up to 70 per cent of coal behave much the same as charges containing 100 per cent coke. With 70 per cent of coal in the mixture he obtained production capacities from the 8-foot 6-inch sets up to about 92 per cent of the nominal rated capacity; and with straight coal about 81 per cent of the rated capacity. The fuel consumption with 70 per cent of coal in the mixture was about 24 per cent higher and with 100 per cent of coal about 50 per cent higher than with coke alone. The coal was from Franklin County, Ill., and the coke was gas-retort coke made in St. Louis from eastern coals.

TESTS AT OTTAWA, ILL., AND BELOIT, WIS. (SECOND SERIES)

In 1922 the writer of this paper made some tests with coal and with coal and coke mixtures in the gas plant at Ottawa, Ill. Simultaneously Krumrey made tests at Beloit, Wis., with coal and coke from the same sources. The detailed results of both investigations were reported in the 1922 Proceedings of the American Gas Association.[2] In the Ottawa tests production capacities up to 97.5 per cent of the rated capacity were obtained with 70 per cent of coal in the mixture and 10 hours daily operation. With 100 per cent of coal, 93.6 per cent of the rated capacity was obtained. The fuel consumption with 70 per cent of coal was slightly less than with 100 per cent of coke, and the fuel consumption with 100 per cent of coal was only about 5½ per cent higher than with 100 per cent of coke. The oil consumption was about the same in all trials.

[2] Report of the American Gas Association subcommittee on the "Use of coke and bituminous coal mixtures as water-gas generator fuels." C. W. Bradley, chairman. Am. Gas. Assoc. Monthly, January, 1923, pp. 49–59.

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At Beloit the conditions were slightly different from those at Ottawa, the blast pressure being a little lower and the operating cycle longer. The gas-production rate decreased regularly as the percentage of coal in the mixture increased. The fuel consumption increased with increasing percentage of coal in the mixture, as did also the oil consumption. With 100 per cent of coal, however, the consumption of oil was less than with any of the fuel mixtures. No run was made with 100 per cent of coke, therefore no direct comparison can be made between coke and coal fuels under existing plant conditions. The gas production with 67 per cent of coal in the mixture was about 79 per cent of the nominal capacity of the set and with 100 per cent of coal was about 65.5 per cent. The blast pressure available, however, was only 24 inches of water pressure under the grates, whereas the nominal rated capacity assumes a blast pressure of 36 inches. The fuel consumption per 1,000 cubic feet of gas in the Beloit test with 66.7 per cent of coal in the mixture was little if any higher than might have been expected with 100 per cent of coke of the quality employed under prevailing conditions. The fuel consumption with 100 per cent of coal was about 22 per cent higher than would have been expected with 100 per cent of coke.

USE OF COAL IN LARGER SETS

In addition to the tests heretofore mentioned, a few companies have tried out coal fuel in larger sets, but, except for the tests about to be described, the writer knows of no reported experiments made under carefully observed conditions.

In large water-gas sets, as in other large production units, efficiencies might be expected to reach their highest point. Experience has shown, however, that with coal fuel in the larger sets certain conditions develop that work against best results. Although these conditions are recognized, means of overcoming them have been but partly successful to date. The main purpose of this paper is to discuss these conditions, the measures that have been taken to remove them, and the net technical and economic results.

WATER-GAS PLANT AT JOLIET, ILL.

The water-gas plant of the Coal Products Manufacturing Co. at Joliet, Ill., is one of the most up-to-date in this country. In 1923 the plant consisted of five 11.0-foot (external diameter) sets, connected to five vertical fire-tube waste-heat boilers. The sets have a nominal capacity of 3,500,000 cubic feet of gas each per 24 hours with good coke as fuel and a blast pressure under the grates of 42 inches of water. In addition to the waste-heat boilers the plant has other features that favor fuel economy. Exhaust steam from

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the turbine-blower units, pumps, and other steam-using machinery passes into an exhaust-steam header and is used in the sets at a pressure of 7 to 8 pounds during the steaming part of the operating cycle; any deficiency is made up by steam from the high-pressure header of the waste-heat boilers reduced (by reducing valves) from about 125 pounds per square inch to the pressure of the low-pressure header. Results have shown that enough steam is "stepped down" from the high-pressure header to superheat the low-pressure steam several degrees.

AUTOMATIC CONTROLS

As a further aid to operating efficiency the sets are equipped with automatic controls. These electrical devices, operating by means of hydraulic (and oil) pressure cylinders, carry out the predetermined cycle of operation with only supervisory attention by the water-gas makers. Thus the various parts of the cycle follow each other with mathematical precision and with the greatest expedition, reducing to a minimum the time lost in changing valves. Although few if any automatic mechanisms are infallible, those at Joliet are understood to have given little trouble. Their operation during the course of a day's run usually has to be stopped only when it is necessary to coal the fire, remove ashes and clinker, or shut down for repairs.

PYROMETERS, PRESSURE REGULATORS, AND METERS

In addition to the automatic controls the sets are equipped with pyrometers for indicating temperatures in the oil-fixing chambers, and with pressure regulators to maintain constant pressure in the air-blast main during the blow period of operation. The sets are also equipped with air, steam, and oil meters, which are now considered essential in all up-to-date water-gas sets.

WASTE-HEAT BOILERS

The waste-heat boilers are set just outside the water-gas house; they are of the vertical fire-tube type and each has one hundred and ninety-two 4-inch tubes. The boilers are so arranged that both the blast gas and the make gas can be passed through them, or if for any reason it is desired that only the blast gas pass through, the make gas can be diverted to the relief holder through a wash box inside the water-gas house.

TERTIARY AIR SUPPLY

To burn any blast gases that may have passed the checker chambers unburned, a tertiary air supply is introduced near the top of the superheater. This tertiary air supply is most important when

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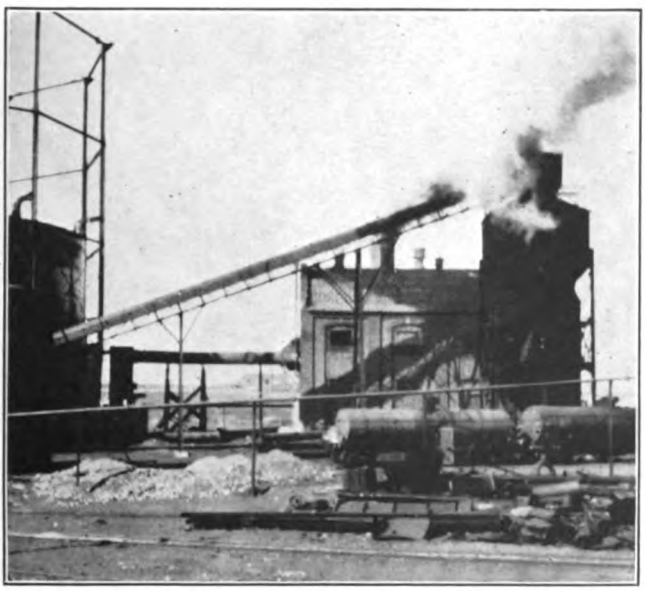
A. WATER-GAS FUEL BUNKER; CAR-LOADING AND WEIGHING PLATFORM ON LEVEL WITH OPERATING FLOOR



B. WATER-GAS PLANT OF COAL PRODUCTS MANUFACTURING CO., JOLIET, ILL., BEFORE INSTALLATION OF WASTE-HEAT BOILERS

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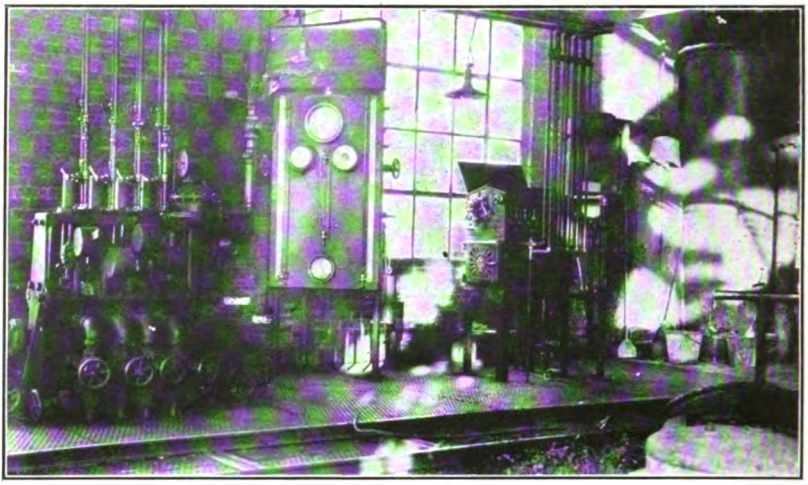

A. CRITCHLOW VALVE NEST, GAUGE BOARD, AND AUTOMATIC CONTROL FOR ONE SET

B. TURBINE-BLOWER UNIT FOR SUPPLYING AIR BLAST TO ONE SET

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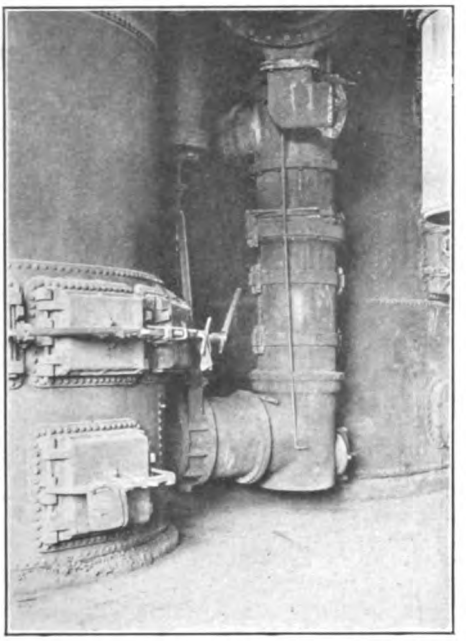
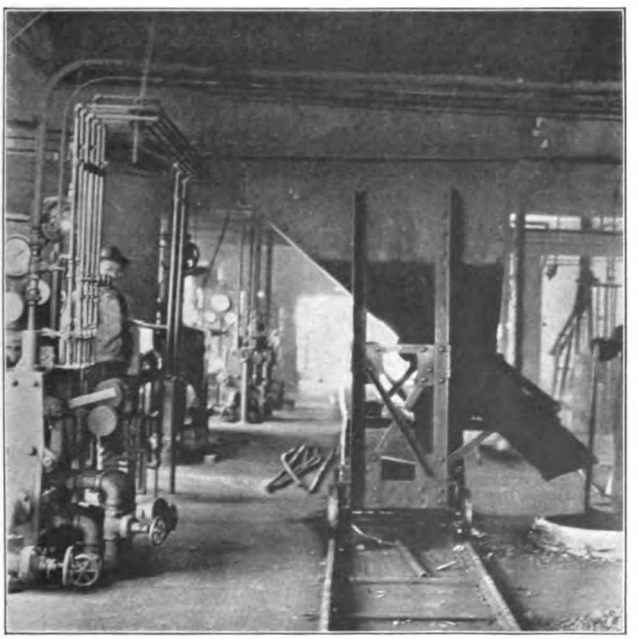


A. LOWER PART OF WATER-GAS SET WITH DOWN-RUN CONNECTION



B. CAR FOR CHARGING GENERATOR

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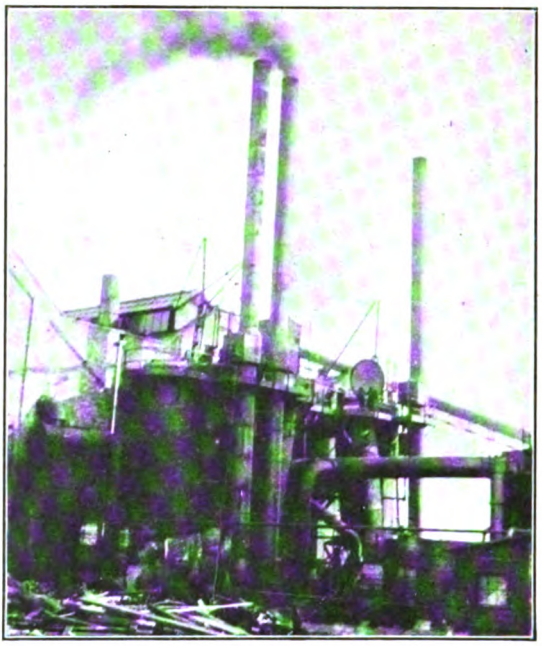
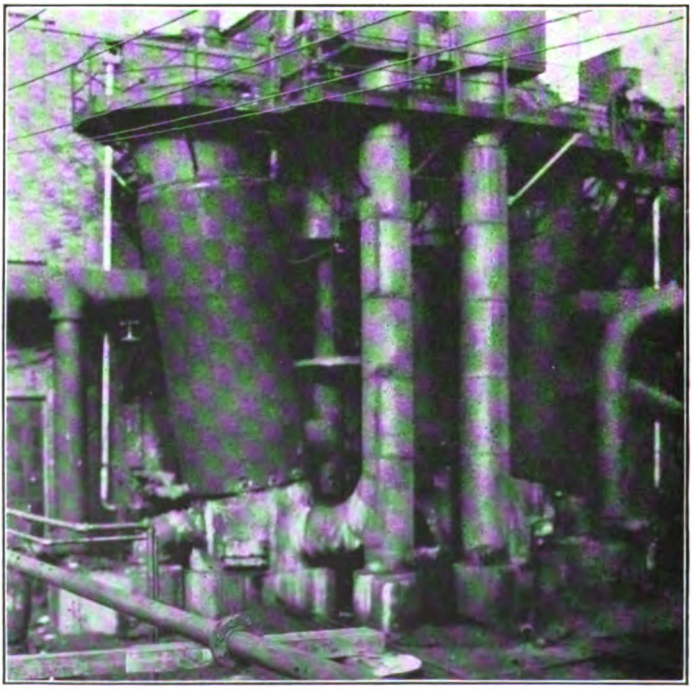


A. THREE WASTE-HEAT BOILERS CONNECTED TO WASTE-GAS SETS AT JOLIET



B. NEAR VIEW OF TWO WASTE-HEAT BOILERS

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bituminous coal is the generator fuel, because to burn in the checker chambers all of the volatile matter liberated from the coal is impracticable. With the present arrangement the upper part of the superheater, the connection to the waste-heat boiler, and the part of the boiler above the upper tube sheet serve as a combustion chamber. During the blast period the combustion products from the set pass from the top of the superheater downward through the tubes of a waste-heat boiler and then up a tall stack. When the steam run or make period is in progress, the make gas takes the same course through the boiler, but as the stack is closed at this time by a valve about halfway up on the pipe the gas passes from the bottom of the boiler through a water seal in an outdoor wash box and thence to the relief holder.

STEAM HEADER

The steam header of the waste-heat boilers is connected to the header of a coal-fired boiler plant in a neighboring building; any surplus developed by the waste-heat boilers goes to help out the load of the coal-fired plant and similarly the latter plant, when occasion demands, makes up any deficiency of steam generation by the waste-heat boilers.

STACKS

The stacks of the waste-heat boilers are equipped with high-reading recording thermometers; excessive accumulations of deposits on the tubes are at once indicated by the rise of stack temperature, and can be removed when they become troublesome. Usually when the boilers are running steadily and both blast and make gas are passing through them, the tubes must be cleaned with a turbine cleaner about every two to three weeks. The cleaning takes about two days.

The accompanying illustrations (Pls. I, *A* and *B;* II, *A* and *B;* III, *A* and *B;* and IV, *A* and *B*) show the equipment in the Joliet plant.

OPERATING CONDITIONS

With the present equipment each set must operate as nearly full time as possible to meet the demand for gas. Theoretically, full-time operation should show the best possible performance. The Joliet plant therefore affords what has not been available in any of the other installations mentioned—an opportunity to study performance. Unfortunately a study of the use of coal and coke mixtures in this plant has been impracticable because of lack of facilities for getting uniform mixtures of both fuels to the sets. However, it has been possible to experiment with coals of a few different types,

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including Illinois and West Virginia, so that some interesting comparisons can be made.

COAL HANDLING

As the water-gas plant at Joliet uses about 100 tons of generator fuel a day, coal-handling labor must be reduced to a minimum. Hopper-bottom coal cars are run over a track hopper, whence the coal is carried by a belt conveyor to an overhead bunker (Pl. I. *A*). From this bunker the coal is drawn off through a valve into lorries running on an industrial railway parallel to a line through the coaling holes of the five sets. The coal runs from a lorry through a side spout extending over the coal hole of the set and is distributed over the fuel bed by a scoop of special design.

Although the coal-handling equipment described permits fuel to be handled at low cost, it has the disadvantage of causing breakage of coal. The coal is dropped four times from railroad car to fire, and the drop from conveyor to bunker may be as much as 30 feet if the bunker is nearly empty. Most of the coals used in the plant break easily and show a high percentage of fines when subjected to the standard shatter test used for coke. Another unfavorable condition that has prevailed since the plant began to use coal fuel is the uneven sizing of the coal. At smaller plants in all the tests heretofore described the coal—usually sized—was forked by hand into the charging lorries. At the Joliet plant, however, the coal has included all sizes from slack to lumps 8 to 10 inches on a side. Such an assortment has been present in almost every lorry load. It is evident that one prerequisite of best water-gas operation, coal of suitable and uniform size, has been lacking. Just how unfavorable this condition has been is somewhat problematical, since the coal has usually tended to break to very small pieces in the fuel bed before it is completely coked.

CHANNELING OF FUEL BEDS AND BLOWING OVER OF FUEL

The breaking of coal during handling and in the generator, with the lack of uniformity in fuel size, and the tendency of the blast to channel through the fuel bed at its circumference, have led to most of the mechanical and chemical difficulties experienced in operating large sets with coal fuel. One result of these causes is the blowing over of partly coked fuel from the generators to the oil-fixing chambers.

This tendency to blow fuel over into the checker chambers seems to be explainable as follows: The formation of a channel through the fire gives a path of least resistance to the air and steam; the resultant velocity through the channel is high. By this high velocity

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larger pieces of fuel are carried than would be carried if the steam and air passed through the fuel bed uniformly. When conditions were worst at Joliet as much as 10 per cent of the fuel charged was carried into the checker chambers, in spite of the fact that the dust collectors on the connections between the generator and superheater were emptied regularly before they had become full. Why the dust

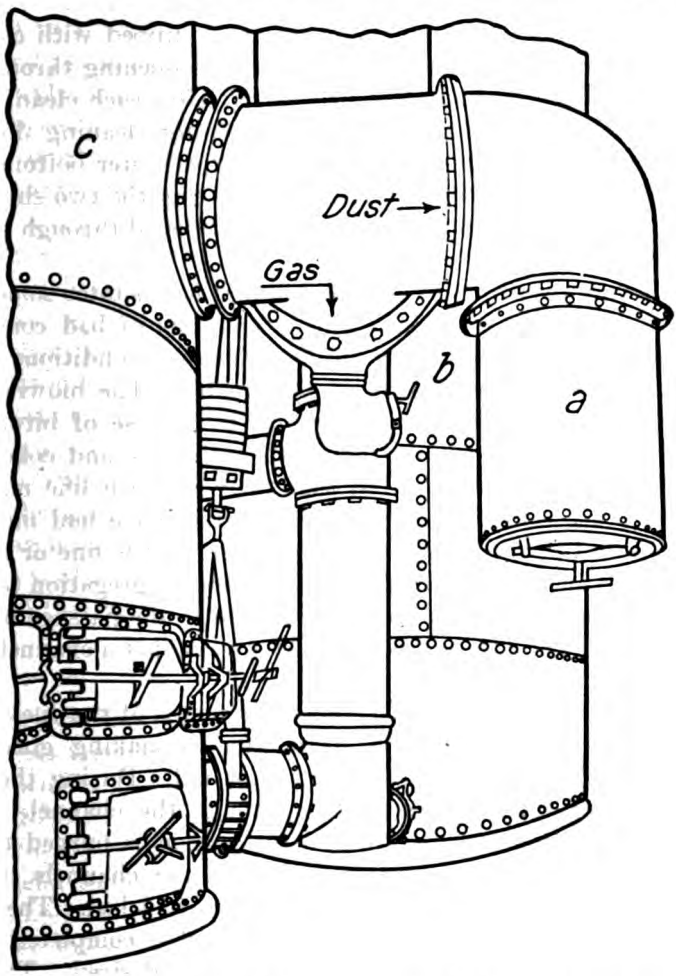

FIGURE 1.—Arrangement of dust collector on generator off-take: *a*, Dust collector; *b*, carburetor; *c*, generator.

collectors failed to stop the blown-over fuel as long as they were not filled is rather difficult to explain. Figure 1 shows the arrangement of the dust collectors. Since the gases leaving the generator *c* must change their course 90° before passing into the carburetor *b*, it is calculated that the particles of fuel on account of their higher specific gravity will continue in the original direction of travel and drop

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into the dust collector *a*. This dust collector has a closed bottom which can be removed to dump the contents.

Although the dust collector does remove much solid material from the gas current, a large proportion passes on. A small amount of that which is carried into the carburetor is deposited on top of the checkerwork, but the larger part sifts through and is deposited in the bottoms of carburetor and superheater and in the tunnel connecting them. The bottoms of these chambers are equipped with cleaning doors. The original doors were oval, and the opening through the brick lining of the set had to be bricked up after each clean, which required much time. Eventually quick-opening cleaning doors of large size were set on the rear side of the superheater bottoms. As these doors are in line with the tunnel connecting the two shells, the tunnel and bottoms of both chambers can be cleaned through the one opening.

This blowing over of fuel is annoying and necessitates some extra labor, but as already mentioned it is a symptom of bad conditions rather than in itself a bad condition. Fuel-bed conditions in the generator obviously cause much of the trouble. The blowing over of fuel at high pressures is not peculiar to the use of bituminous coal. It occurs to a certain extent with anthracite and coke, especially if they are so poorly sized that there is much fine material. Attempts to use coke breeze for generator fuel have had much the same results. In general, it seems that when fuel is fine or a large proportion of fine fuel is mixed with the coarse, segregation tends to increase. Then the resistance of the fuel bed to the passage of blast and steam differs at different points. At a weak spot a channel burns through.

Once a channel has developed, the effectiveness of the fuel bed in decomposing steam during the steam run in making good producer gas during the blow is greatly impaired. During the blow a large part of the air blast passes through the channel. Much localized combustion takes place and the carbon is burned to CO_2 instead of CO. This combustion begun in the channels may be largely completed in the generator above the fuel bed. The result is that too much of the combustion of the fuel is completed in the generator and not in the checker chambers as desired. The tendency, then, is to overheat the generator top, including the coaling sleeve and lid and the upper hot valve, and thus cause their premature failure.

ATTEMPTS TO OVERCOME FUEL CHANNELING

Remedial measures can be applied in three ways. The first and most logical is to prevent the formation of channels; the second, to fill them up as soon as possible after they are found; and the third,

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to attempt to remedy the results. Experiments in all three directions have been tried but without complete success. As stated above, the segregation of fuel into different sizes appears to be one of the main causes of channeling. The remedies that naturally suggest themselves are: 1, Size the coal and eliminate all fine material; 2, distribute the fuel in the generator so that the fine coal which seems to offer the most resistance to the passage of blast and steam goes to the periphery of the fuel bed where the tendency to channel is greatest; 3, direct the blast and steam away from the periphery of the fuel bed; 4, diminish as far as possible any other conditions which tend to cause or aggravate the channeling.

Obviously all four of these remedies should be applied if possible, but plant conditions have to be considered. In the Joliet plant it has not been practical thus far to size the coal, at least where sizing would give the greatest promise of being effective. As stated before, the coal breaks easily and there seems to be no practical way of eliminating the long drops it must take on its way to the sets. The fact that the coal usually breaks up into very small pieces in the generator, even before coking is complete, seems to give no certain promise of improved results from screening the coal, even if screening were practicable. The coals employed heretofore have been chiefly those obtained from the company's own mines. Since the plant has used the whole mine output for coking, until recently there has been no reason to install extensive screening facilities at the mines. Other coals would show possibly better results than the coals employed, though this can not be affirmed with certainty.

DISTRIBUTION OF FUEL

The distribution of fuel over the surface of the fire is important and does much to improve conditions although it by no means stops the formation of channels. Since the blast and steam have a tendency to pass up around the periphery of the fuel bed, leaving an unburned core in the center, a fuel spreader should be used which will tend to pile the fuel up around the generator wall and leave the center of the fuel surface lower than the circumference. In the smaller water-gas sets this is usually accomplished by the use of a cone spreader such as is illustrated in Figure 2, but an 11.0-foot set which has an internal diameter of 9.0 feet has for mechanical reasons a coaling hole somewhat smaller in proportion to generator diameter than a set with an internal diameter of about 4.0 feet.

A cone spreader that can be lowered into the coaling branch of an 11.0-foot set is not large enough to deflect the coal to the circumference of the fuel unless the angle of the slope of the cone to the

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vertical axis is low, then the cone is flat, and coal will not leave the cone in the direction of its slope unless it falls on the cone from a height sufficient to give a high velocity. Such a height of fall is usually impractical because of increased breakage and the design of the lorries used with the large sets. The spreading device shown in Figure 3 was effective in placing the fuel where needed. The hand chute or scoop could be guided by the operator who by raising or depressing the handles was able to throw the coal to any part of the fuel-bed surface. Placing coal around the circumference of the fuel did not prevent the formation of channels there but doubtless diminished them.

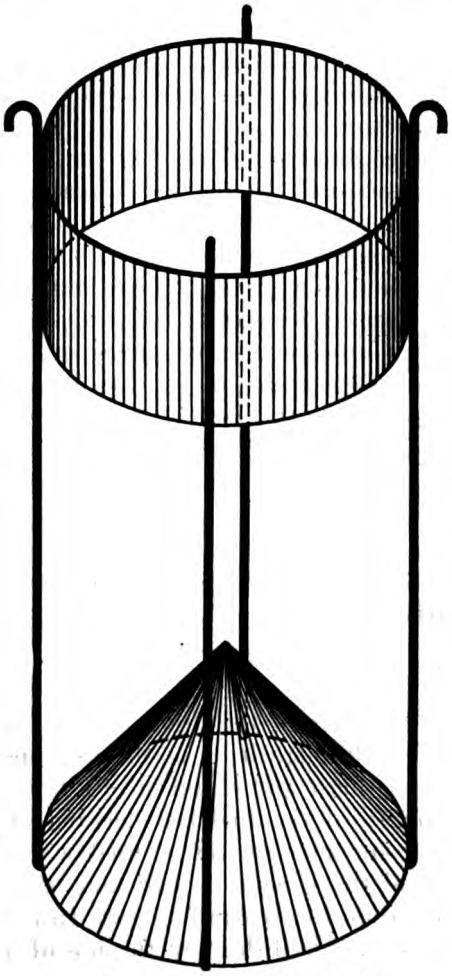

FIGURE 2.—Cone fuel-spreader

FILLING CHANNELS IN THE FIRE

Another method of diminishing the effects of channels is to fill them as soon as discovered. This can be accomplished in two ways—by filling with green fuel or by barring. When green fuel is put into a channel in the fire, it fills that particular void, but is also likely to make that part of the fuel bed more resistant to the blast and steam than others, with the result that a new channel forms elsewhere. If, on the other hand, coked fuel from a high part of the fuel bed is placed on the void and tamped into place with a bar, the fuel bed seems to acquire a more uniform resistance to the passage of air and steam, with the result that new channels do not form so easily. Even this procedure does not seem to do away entirely with channeling when bituminous fuel is used in large sets. In fact, nothing has been entirely effective in preventing channels.

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Barring a fire is a hard, hot job at best and is more difficult with bituminous coal than with low-volatile fuel, since volatile matter is being evolved from the fuel continually, even several runs after the preceding charge has been made. This volatile burns in the top of the generator when the coaling lid is open, and flames often rise several feet above the coal hole, making barring almost impossible unless a metal shield covers the greater part of the coaling hole. The flames also make difficult inspection of the fuel bed and location

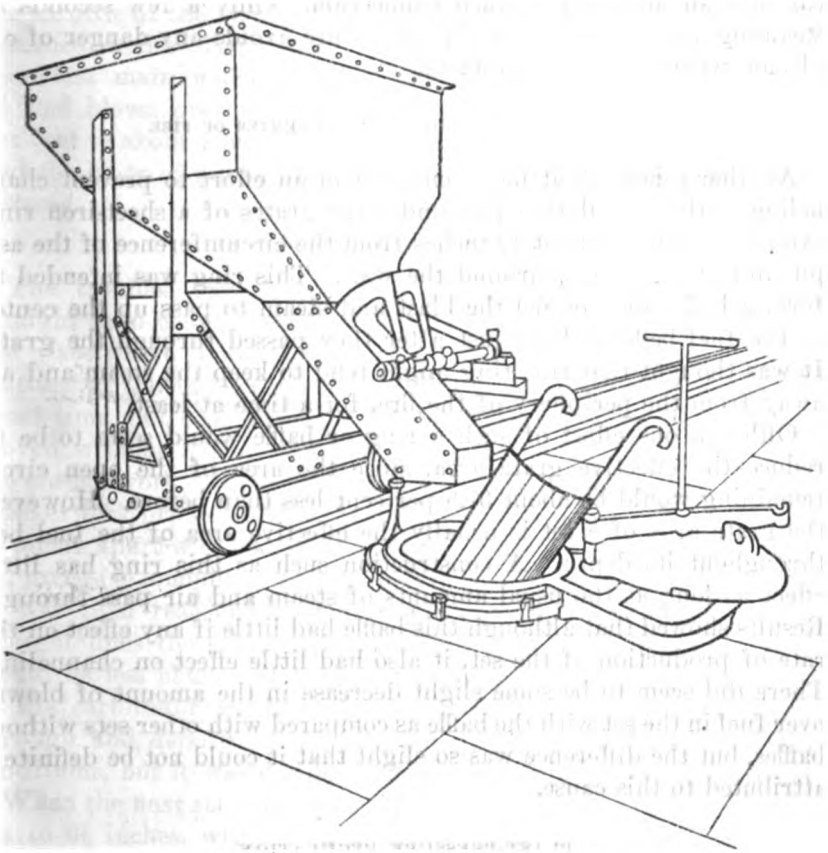

FIGURE 3.—Charging car and hand chute.

of the channels in the fire, so there is a great temptation for operators to neglect barring whenever possible.

In the Joliet plant, the waste-heat boilers with their tall stacks have permitted a procedure ordinarily impossible. The boilers and their stacks create a strong draft in the sets. The hot valves can therefore be reversed during coaling and barring so that the lower valve is open and the upper valve closed. A down draft through the fire is created which does away with the flame and permits good in-

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spection of the fuel-bed surface. While barring the fire even under these conditions is not entirely comfortable on account of the radiant heat from the fuel, still the task is much more bearable than it would be otherwise. It is quite possible that, in the absence of waste-heat boilers, a steam jet of some kind in the superheater top could be devised to create a draft on the set. After the fire is barred and the coaling lid closed, the hot valves are returned to their normal position and the ash pit of the set cleared of combustible gas with steam through an auxiliary 1¼-inch connection. Only a few seconds of steaming are necessary, but this procedure avoids any danger of explosion when blasting is resumed.

DEFLECTING BLAST AND STEAM TO CENTER OF FIRE

Another scheme that has been tried in an effort to prevent channeling is the installation just under the grates of a sheet-iron ring extending inward about 12 inches from the circumference of the ash pit and fitting snugly around the wall. This ring was intended to form a baffle and compel the blast and steam to pass up the center of the fuel bed—at least just after they passed through the grate. It was thought that this ring might tend to keep the steam and air away from the periphery of the fire, for a time at least.

Offhand, one effect of such a ring or baffle would seem to be to reduce the effective grate area, since the area of the open circle remaining would be about 37.5 per cent less than before. However, the grate area of a set is usually the effective area of the fuel bed throughout its depth. A construction such as this ring has little effect as long as the usual amounts of steam and air pass through. Results showed that although this baffle had little if any effect on the rate of production of the set, it also had little effect on channeling. There did seem to be some slight decrease in the amount of blown-over fuel in the set with the baffle as compared with other sets without baffles, but the difference was so slight that it could not be definitely attributed to this cause.

BLAST-PRESSURE REGULATION

Another arrangement, and one that was far more effective, was tried eventually. It was reasoned that fluctuations in the blast pressure might be partly responsible for the formation of channel or at least be instrumental in carrying over more fuel, once a channel was formed. It was the practice in the plant to use only one blower set, of the three installed, to supply air for three or four sets. One blower was able to supply all the blast that could be safely used with coal fuel without blowing over an excessive amount of fuel. The other blower sets could be reserved as spares.

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The result of using one blower for several sets was that if two or more sets at a time were on the blow part of their operating cycle and one was suddenly taken off for a steam run, there was a sharp rise in blast pressure to the other sets. This rise of pressure tended to make the blast break through the fuel bed to form channels; if channels were already present the velocity through them was so increased that much more fuel was picked up and carried into the checker chambers. By means of a pressure regulator working on the throttle of the turbine-blower installations and controlled by the pressure in the blast main it was possible to hold the pressure in the blast main much steadier; then, as anticipated, the amount of fuel blown over was greatly reduced, dropping from about 10 per cent to about 4 per cent of the fuel charged. Results were better and the labor of removing blown-over fuel from the set was greatly reduced.

EXPERIMENTS IN CHECKERING SETS

The troubles experienced from blown-over fuel led to much thought as to whether the bulk of this fuel could not be deposited in the place where it would be most accessible. Coal deposited in the bottoms of the checker chambers could be reached and removed in a short time, but coal deposited in the checkerwork could not be removed without letting down heats on the whole set and removing the checkerwork. When operation with bituminous coal started, the checkerwork bricks were of the usual size and shape and were spaced 3½ inches apart with courses staggered, according to the usual custom. An excessive amount of coke lodged in the spaces between the bricks. It was then reasoned that if the carburetors were checkered in straight flues the oil-fixing area would remain the same but there would be less chance of lodgment, because the coked fuel arriving in the carburetor would have a greater tendency to continue on through and deposit in the bottoms. This arrangement improved conditions, but it was decided to carry the experiment still further.

When the next set was recheckered, the brick spacing was widened out to 6½ inches, with straight flues in both carburetor and superheater. This, of course, decreased the oil-fixing area of the checkerwork and seemed to be reflected in a lower oil efficiency. The next step was to try checkering 6½-inch straight flues in the carburetor and 3½-inch straight flues in the superheater. This carburetor spacing and arrangement, of course, permitted less lodgment of fuel in the carburetor, but the spacing was too wide for best oil-fixing results. It was decided, then, to try bricks of pear-shaped cross section, the assumption being that the tops of the bricks, being very narrow, would decrease the amount of deposit and would still make

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possible a large oil-fixing area. Accordingly a 3½-inch spacing with pear-shaped bricks in straight flues was tried in the carburetors, leaving the superheater bricks the same as before. Bricks of pear-shaped cross section proved hard to lay up and their use did not improve results appreciably.

The last arrangement tried up to the time this report was written, and the one that appears the most promising, is the use in the carburetors of No. 3 arch brick spaced in 3½-inch straight flues and in the superheaters of 9-inch straight bricks spaced 6 inches apart but staggered. With this spacing the average duty of the carburetor checkers between recheckerings is about 1,200 operating hours. The next innovation will probably be the brickless carburetor, into which oil will be injected through a high-pressure spray. It is understood that arrangements for this have already been made. If the method works well it will of course obviate the necessity of changing checker bricks and should result in a decided saving of labor, especially when bituminous coal is used.

OPERATING PROCEDURE

During about two years of operation with bituminous coal, nearly every combination of conditions that gave even remote promise of improving results has been tried. The cycle has been shortened and lengthened, steam and air increased and decreased, and coaling methods varied. Improvement of fuel-bed conditions by barring has been tried; at other times barring has been omitted purposely to determine the effect.

In view of the great variety of operating conditions, results obtained over an extended period would show only average performance without indicating the best method of handling the sets. By comparing these with the results obtained under a selected set of conditions it is possible to learn the tendencies observed after certain changes.

HEAT-BALANCE TEST WITH WASTE-HEAT BOILERS

The waste-heat boilers were not erected until the sets themselves had been using bituminous coal for about a year. By that time operation had become fairly well standardized and it was known just about what efficiencies were obtainable with different kinds of fuel, and what treatment gave best results with each fuel. It has been determined that a much larger percentage of coal fuel was wasted than when coke was used. An enormous loss of volatile matter at the stack was evident, in addition to the loss of sensible heat. Waste-heat boilers offered a logical solution of the problem of utilizing much of the heat that ordinarily was wasted. After the boilers were

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installed the saving in boiler fuel was quite evident, but was hardly as much as would be predicted from tentative calculations. It was decided therefore to make a complete heat-balance test under the direction of the author of this paper to determine the extent of the various heat losses taking place and thus to reduce them wherever possible. The heat-balance test was somewhat complicated by the fact that individual water-gas sets could not be isolated, since there was no way of measuring individual outputs. The test therefore had to be run with three sets and three waste-heat boilers as a unit. During a test this unit was operated according to usual procedure.

NATURE OF THE HEAT BALANCE

A heat balance, as the term implies, is a summarized balance of heat output against heat input. In working out such a balance one must take a certain reference temperature. For convenience a temperature of 60° F. was assumed and the heat input and output above this temperature were measured. Determination of heat input is comparatively simple. Heat enters the set as heat of combustion of coal and oil and as heat in the steam. The incoming materials also bring with them a small amount of sensible heat if their temperatures are above 60° F.

ITEMS OF HEAT INPUT

The separate items of heat input are as follows:

1A. Heat of combustion of generator fuel.
2A. Sensible heat of air blast.
3A. Heat in steam supplied to generators.
4A. Heat of combustion of oil for carburetion.
5A. Heat carried by water vapor in air for blasting.
6A. Sensible heat of coal.
7A. Sensible heat of oil.
8A. Heat in feed water to boilers.

DETERMINATION OF HEAT INPUT

The determination of some of the above items is simple. The heats of combustion of the generator fuel and the oil, items 1A and 4A, are readily determined by calorimeter tests of average samples. Item 2A is more complicated. The air to the generator is metered, but the secondary air to the carburetor and the tertiary air admitted at the top of the superheater are not. Their volumes can be determined approximately by computing the volume of producer gas from its analysis and the volume of primary air used. Knowing the volume and composition of the producer gas and the composition of the gas resulting from its combustion as determined from stack-gas

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analyses, one can compute the approximate volume of the total air blast. The average temperature of the air blast was determined by a thermometer inserted in the blast main. Item 2A is very small and some error due to uncertainty of analyses and measurements could have but slight effect on the grand total of heat input.

Item 3A, the heat in the steam to the generators, was readily determined because the steam to the generators was measured by individual flow meters; its average pressure was determined by a calibrated steam gauge read at regular intervals and its quality, by a thermometer in the low-pressure steam header. Since the temperatures thus read showed that the steam was superheated throughout the test, the heat content was readily obtained from tables.

Items 5A and 6A, the heat carried by the moisture in the air and the sensible heat of the coal, were calculated by taking the temperature and humidity of the air, which gave the necessary data. However, under the conditions of the test, these items were so small as to be negligible. A thermometer in the oil-supply line near the sets gave data for item 7A. The sensible heat in the feed water to the waste-heat boilers, item 8A, was determined by metering the feed water with a hot-water meter of the displacement type, which was calibrated by weighing water passed through it before and after the test and by taking the temperature in the feed-water line near the boilers. The sum of the above items gave the entering heat to be accounted for.

ITEMS OF HEAT OUTPUT

Outgoing heat from water-gas sets must be accounted for in a variety of ways. Part of this heat is the calorific value of products, and part is the sensible or latent heat which is at once dissipated to the surroundings. To measure and allocate the outgoing heat involves the measurement of each separate item of heat loss, which is sometimes complicated by mechanical difficulties of measurement. The total of the following items of heat output must balance the total heat input.

1B. Heating value of finished gas.

2B. Heat in undecomposed steam passing through fire.

3B. Sensible heat in illuminating gas leaving waste-heat boilers.

4B. Sensible heat in blast gas leaving waste-heat boilers.

5B. Heat of combustion of stack gas.

6B. Heat in water vapor in stack gases.

7B. Heat of combustion of partly consumed fuel removed from checker chambers.

8B. Heat of combustion of generator refuse.

9B. Sensible heat of rejected generator and checker-chamber refuse.

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10B. Steam generated in waste-heat boilers.
11B. Heating value of tar.
12B. Sensible and latent heat of tar.
13B. Radiation and convection.

DETERMINATION OF HEAT OUTPUT

Allocating the heat output to these various items involves much labor and numerous calculations. The most convenient way to handle the problem is to consider the sets and their waste-heat boilers as a unit and to measure heat input and output for the entire installation. This procedure does not of course show the performance of a particular set or boiler but does give the performance for the whole plant.

Item 1B, the heating value of the finished gas was readily determined by a recording gas calorimeter (Pl. V, *A* and *B*) built by the Cutler-Hammer Co. The readings were checked daily with a flow calorimeter.

Heat in the undecomposed steam, item 2B, was calculated by observing the average temperature of the make gases leaving the boilers and by determining the amount of water vapor in the gas at the same point. This was done by bubbling the gas through a large weighed bottle of cold water after it had been passed through an asbestos-filled tube to remove tar. Thence the gas passed through a test meter. The tar tube also had been weighed before. Gas was passed through this apparatus during several successive steam runs and shut off while the blast period was in progress. The determination was repeated several times during the main test under different fuel-bed conditions in the same set and with different sets. The tar tubes were freed from water by passing a current of dried air through them for several hours. The loss of moisture was added to that collected in the water bottle. The remaining gain in weight over the weight of the original tar tube gave the tar in the gas. From the temperature and weights of the outgoing water and tar vapors, the heat-carrying capacities were readily computed, the specific and latent heats of water being taken from steam tables and those of tar from reference books. The method employed for determining tar and water is recognized as somewhat inaccurate, but it is believed that a close approximation of the values for items 6B and 12B was obtained.

The heat output, as heating value of the tar (item 11), was readily ascertained by collecting a sample during the test run and determining its heating value, which was multiplied by the weight of tar per 1,000 cubic feet of gas as determined in the manner just described.

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Item 3B, the sensible heat of the illuminating gas, was calculated from the average composition of the gas as determined by analysis and the temperature of the gas at the outlet of the waste-heat boilers, as observed by pyrometers; the volume was measured by the station meter.

The sensible heat of the stack gases was more difficult to determine since no means of metering these gases was available. The average heating value of the stack gas per cubic foot, item 5B, was determined from an average of about 65 stack-gas analyses. The carbon content of the gas could also be computed from analysis. The amount of carbon entering the sets was determined from an ultimate analysis of the coal and oil consumed. The amount leaving could be ascertained by analyses of blown-over fuel removed from checker chambers and of refuse from generators. The carbon in the tar was determined by analysis. The carbon in the finished gas was estimated from analysis. By construction of a carbon balance it was possible to make a fairly close estimate of the amount of carbon to be accounted for in the stack gas, from which it was easy to determine the total volume after the carbon content per cubic foot was computed. The amount of carbon deposited on the checkerwork and on the boiler tubes could not be accurately estimated but it is unlikely that the amount was enough to affect the total materially. From the estimated volume of the waste gas and its known composition, temperature, and calorific value per cubic foot, the total sensible heat, item 4B, as well as the total calorific value could be determined readily.

The water vapor in the stack gas was not measured directly but was determined by working out a hydrogen balance of operation. The hydrogen content of the ingoing materials was readily computed, for their weight and composition were known. The hydrogen content of all the outgoing products was also calculated readily, except that of the water vapor in the stack gases, which was determined by difference. The hydrogen balance is given on page 27.

The steam generated by the waste-heat boilers, item 10B, was computed by measuring the water to the boilers with a Worthington displacement meter (Pl. VI, *A*) for hot water. This meter was new and was calibrated by weighing a measured volume of water passed through it before and after the test. The amount of water blown down from the boilers—water that had been heated to boiler temperature but not evaporated—was determined by measuring the volume blown down between two marks on the water gauge and computing the weight of water to which the calculated volume was equivalent at the temperature corresponding to boiler pressure. The weight of the blown-down water was deducted from the total

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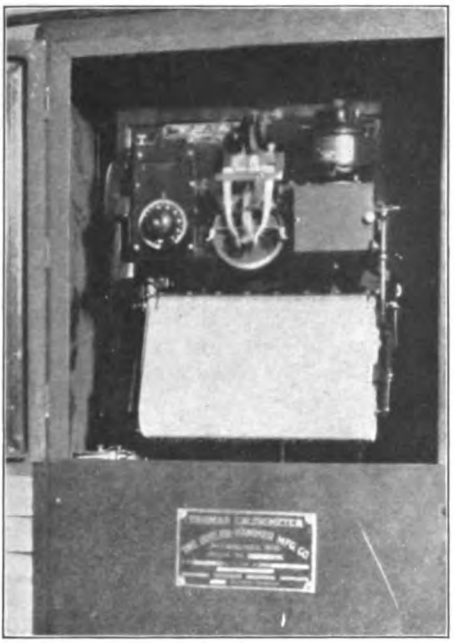
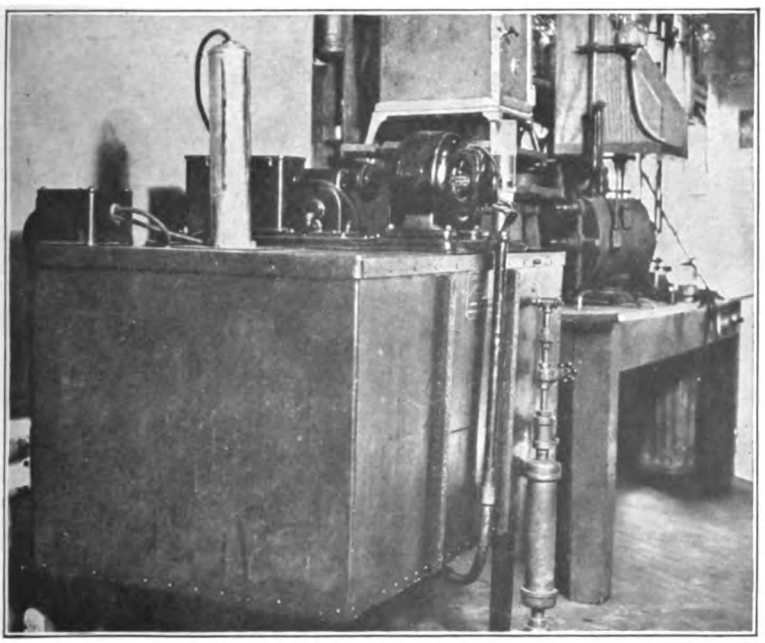


A. RECORDER OF THOMAS GAS CALORIMETER



B. THOMAS RECORDING GAS CALORIMETER

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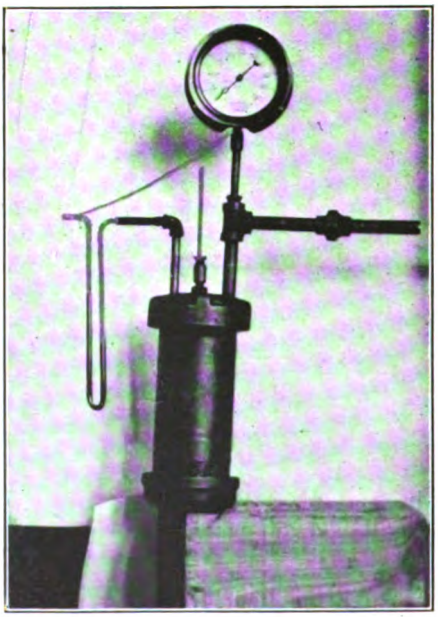
A. WORTHINGTON DISPLACEMENT WATER METER



B. "HOMEMADE" STEAM CALORIMETER (THROTTLING) AS ASSEMBLED, BEFORE LAGGING

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weight as metered and the heat of liquid of the blown-down water above 60° F. was added to the total heat of the steam generated.

The sensible heat of the generator and checker-chamber refuse, item 9B, was estimated by thrusting a pyrometer into the refuse before it was removed. The weight of both the generator refuse and the refuse from the checker chambers was determined. A specific heat of 0.2 B. t. u. per pound per degree F. was assumed.

Item 11 B, the heating value of the tar, was determined readily by calorimeter. Since the total weight had been determined, as previously discussed, the total heat value could be determined.

The radiation and convection losses, item 13, could not be readily determined directly. The figures used were taken from data supplied by the United Gas Improvement Co., which estimated radiation and convection loss at 500,000 B. t. u. an hour from an 11.0-foot water-gas set, 200,000 B. t. u. an hour from a waste-heat boiler, and 88,000 B. t. u. an hour from the connections. The company says that the total loss from several sets may be assumed to be the total loss per set, as above, multiplied by the number of sets.

The difference between the heat input as computed and the sum of the heat-output items was taken as the unaccounted-for heat. It is realized that some of the determinations are not exact, but it is believed that the distribution of the heat losses as determined represents actual conditions with fair exactness.

APPARATUS USED IN TEST

The pieces of apparatus used for making the various measurements necessarily differed somewhat in degree of accuracy. When possible the measuring instruments were calibrated before a test. This could be done for pressure gauges, pyrometers, thermometers, scales, the gas meter for the finished gas, the water meter, and the calorimeter, but it was not feasible to calibrate the steam meters measuring the steam input to the sets and the air meters measuring the air input. Care was taken to see that the zero points were correct. The steam meters were Republic flow meters; the air meters were of the Venturi type.

Gas analyses were made with two instruments, a Bureau of Mines type of gas-analysis apparatus and a Morehead gas burette. Stack temperatures were determined by three base-metal couples in wells extending to the middle of the stack at the outlet of the boiler. The temperature of the illuminating gas leaving the waste-heat boiler was measured by pyrometers placed in wells in the gas outlet between the boilers and the wash boxes.

The quality of the steam in the high-pressure header was determined by a throttling calorimeter (Pl. VI, *B*) connecting into the header.

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PROCEDURE IN HEAT-BALANCE TEST

The test started at 6 a. m. and continued 144 hours. The day was divided into two 12-hour shifts, with five observers on each shift. For such a variety of observations as a heat-balance test of this kind entails, a larger testing force is recommended, but no more men were available at the time. On each shift one man spent his entire time making gas analyses. It was found that 12 gas analyses a shift for each man were about all that could be done when time was allowed for renewing the absorbing solutions and making the necessary frequent repairs to the combustion pipettes. Another man made four gas analyses a shift and spent the rest of his time collecting gas samples. In all, 192 gas analyses were made during a 144-hour run. They included analyses of finished gas, of blue gas sampled at the generator lid, of blast gas at the same point, and of stack gas from the base of the stacks. Since three sets were running and each was discharging its gases into a separate boiler and through an independent stack, the samples taken had to be distributed with regard to set, time, and kind of gas. Sixteen samples of gas per 12-hour shift would hardly be considered a requisite number for a short test, but it is reasonable to suppose that during a six-day period, if operating conditions remained fairly uniform, the general average for each kind of gas would represent average performance fairly well.

A third man on each shift observed the several instruments employed according to a previously arranged schedule. He read the water meter at the end of each shift and made other readings at about 2-hour intervals. The apparatus included high and low pressure steam gauges, waste-heat boiler pyrometers (six in all), and a throttling calorimeter. Air-temperature, oil-temperature, and air and steam meter readings were also made as a check on the gas makers. This man also determined the moisture and tar content of the gas.

A fourth man watched operation carefully to see whether the air and steam were kept at the predetermined pressure, and if not, what the average variations were. The sets were run for a greater part of the time by United Gas Improvement Co. automatic electric controls. At times, however, the predetermined cycle of operations had to be changed from that set and this observer noted these changes and observed what average cycle the automatics were maintaining.

The fifth man weighed all the fuel and the refuse from the sets and took samples for analysis.

Throughout the test the operation was maintained as nearly uniform as possible; consequently the results obtained represent the conditions then prevailing.

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CONDITIONS AND RESULTS

The conditions and the results shown by the test may be summarized under two heads: First, the operating conditions and the fuel efficiencies obtained; and second, the heat balance which shows where heat losses occur. The heat balance obviously includes all the fuel results realized, but the operating conditions are not of direct interest, though they are in many ways indirectly responsible for the allocation of heat loss among the items of the heat balance. The daily report of water-gas plant operation ordinarily includes the items to be tested under the first head. The heat balance is seldom made in everyday operation on account of its complexity, but is very useful in analyzing a process and locating losses that are not wholly evident from operating results; being, as the term implies, a balance of heat output against heat input, it should show only a small unaccounted-for item due to experimental error. In a thorough analysis of results a number of balances may be constructed which will show certain things about the process. For example, the carbon balance and the water balance show the disposal of the fuel and the water (steam) put into the process. The heat balance, however, is most complete and shows best the value of a process with respect to thermal efficiency.

Table 1 gives the operating conditions and the results for the six-day test period.

TABLE 1.—*Conditions and results during heat-balance test period*

Operating Conditions		
Number of sets operated		3
Size of sets, external diameter	feet	11
Single-pass vertical waste-heat boilers		3
Hours of operation a day—continuous except for cleans.		
Fuel used, Gus Blair lump from Murphysboro, Ill.—four days; Rex lump from Ethel, W. Va.—two days.		
Total duration of test	hours	144
Total fuel used	pounds	1,330,378
Oil used, 32° to 34° B. Oklahoma	gallons	107,305
Operating cycle—1.9-minute blow, 0.2 minute blow run, 2.65-minute steam run, 0.17-minute air purge.		
Division of steam run—all runs split, 1.1 minutes down and 1.55 minutes up.		
Coalings—2,400 pounds of fuel to each set at intervals of about seven runs.		
Temperatures carried:		
Top superheater	° F	1,373
Bottom superheater	do	1,347
Stack gases (blast)	do	956
Make gases (run)	do	726
Oil to sets	do	93
Boiler feed-water	do	122
Low-pressure steam	do	267
Total feed water to waste-heat boilers	pounds	2,923,647

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Heating values:		
Generator fuel, per pound	B. t. u.	12,465
Gas oil, per pound	do	19,575
Tar made, per pound	do	16,750
Gas made, finished, per cubic foot	do	561
Gas blast at generator, per cubic foot	do	67
Blue gas, average, per cubic foot	do	336
Blow-run gas, per cubic foot	do	93.7
Air-purge gas, per cubic foot	do	36.2
Stack gas, per cubic foot	do	23.2
Pressure average:		
Low-pressure steam	pounds	7.3
High-pressure header steam	do	114.0
Humidity of air at 65° F	per cent	50

Results

Total gas made	cubic feet	28,947,000
Gas made per running hour, per set	do	80,800
Gas made per run	do	7,609
Gas made per hour per square foot of grate area	do	1,265
Generator fuel used per 1,000 cubic feet of gas made	pounds	46.0
Blown-over fuel recovered per 1,000 cubic feet of gas	do	4.78
Ashes and clinker recovered per 1,000 cubic feet of gas	do	4.20
Net fuel consumed per 1,000 cubic feet of gas	do	37.02
Oil used per 1,000 cubic feet gas made	gallons	3.72
Heating value of gas per cubic foot	B. t. u.	561
Steam used per 1,000 cubic feet of gas	pounds	50.5
Air used in generator per 1,000 cubic feet of gas	cubic feet	1,979
Tar produced per 1,000 cubic feet of gas	pounds	3.76

Inspection of Table 1 reveals a number of points in connection with operation which are unfavorable in comparison with the results of operation with coke or anthracite. For example, when good coke is used, a production per running hour of about 165,000 cubic feet of finished gas might be expected, with a consumption of about 30 to 32 pounds of coke per 1,000 cubic feet of gas made and an oil consumption of perhaps 3.0 to 3.2 gallons to produce a 561–B. t. u. gas. Moreover, the steam used in the generator would not be expected to be much more than 28 to 30 pounds per 1,000 cubic feet of gas made. The generator blast also is higher than is ordinarily considered good practice with low-volatile fuel; in good practice with coke the volume of generator blast should not exceed 1,300 to 1,500 cubic feet per 1,000 cubic feet of finished gas.

ANALYSES OF FUELS AND PRODUCTS

As stated before, the construction of a heat balance required the determination of the calorific value of the fuel and oil used and of the gases, tar, and solid residues resulting. The analyses of fuel oil, tar, and the solid residues were made in the fuel laboratory of the

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Bureau of Mines at Pittsburgh. The analyses and heating values of the solid materials are shown in Table 3.

The oil and tar were tested for heating value, specific gravity, and sulphur; their carbon and hydrogen contents were also determined in order that a carbon balance and a water balance of operation might be made. The analyses of tar and oil are as follows:

TABLE 2.—*Analyses of gas oil and tar, per cents by weight*

	Gas oil	Tar
Carbon	83.75	89.00
Hydrogen	12.96	5.57
Sulphur	.68	1.13
Heating value, B. t. u. per pound	19.575	16.750
Specific gravity	.860	1.210

TABLE 3.—*Analyses of coals, blown-over fuel, and generator refuse; moisture-free basis*

	Heating value B. t. u. pound	Sulphur	Proximate analysis			Ultimate analysis					
			Volatile matter	Fixed carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulphur	Ash
Gus Blair lump [a]	13,618	1.3	35.2	57.9	6.9	4.9	76.8	1.7	8.6	1.2	6.8
Blown-over fuel	11,257	.6	1.4	79.8	18.8						
Generator refuse	3,885	.4	1.6	29.3	69.1						
Rex lump [b]	13,177	.7	33.3	54.4	12.3	4.9	73.6	1.4	7.5	.7	11.9
Blown-over fuel	11,760	.5	1.1	81.7	17.2						
Generator refuse	1,975	.1	.8	13.4	85.8						

[a] Mined at Murphysboro, Jackson County, Ill. [b] Shipped from Ethel, W. Va.

As stated before, the gas analyses were made at the plant. Table 4 gives the various averages.

TABLE 4.—*Average analyses of gases*

	Finished gas	Blue gas		Blow-run gas	Air-purge gas	Blast gas	
		Up run	Down run			Generator	Stack
CO_2	5.4	6.7	4.3	9.5	13.0	14.4	10.2
Illuminants	10.9	0.8	0.5	0.4	0.6	0.3	0.1
O_2	0.9			1.7	2.1	1.5	7.4
CO	21.7	34.4	35.4	12.0	0.7	8.3	1.5
CH_4	15.3	4.8	4.3	1.8	1.4	1.9	1.3
H_2	25.5	49.5	50.6	7.7	0.8	4.4	0.9
N_2	20.3	3.7	4.9	66.9	81.4	71.2	78.6
B. t. u. calculated [a]	556	338	335	94	36	67	23
B. t. u. by calorimeter	561						

[a] A value of 2,280 B. t. u. for illuminants was computed from a number of analyses and B. t. u. tests. This value was used throughout in computing heating values from analyses.

CARBON BALANCE

In order to compute the volume of the stack gases so as to determine the amount of heat output for which these gases were re-

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sponsible a carbon balance was worked out. The carbon input was readily determined from the weight and the composition of the coal and oil used. For each 1,000 cubic feet of finished gas 46 pounds of coal was used on the as-received basis, or 42.5 pounds on the moisture-free basis. The average carbon percentage of this dry fuel (the Gus Blair and Rex analyses being weighted in proportion to amounts used) was 75.7, making the carbon contribution of the generator fuel 32.17 pounds per 1,000 cubic feet of gas made. The oil used amounted to 3.72 gallons, or 26.7 pounds per 1,000 cubic feet of gas made. The carbon content of the oil was 83.75 per cent, or 22.36 pounds per 1,000 cubic feet of gas, hence the total carbon input was 54.53 pounds per 1,000 cubic feet of finished gas.

The carbon output is distributed among the generator refuse, checker-chamber refuse, tar, finished gas, and blast gas. A small amount of carbon remains in the set as a deposit on the checkerwork. Ultimate analyses of the solid residues were not made, but since they contain only a very small amount of volatile matter it is safe to assume that the fixed carbon plus half of the volatile matter is the total carbon.

The generator refuse removed amounted to 4.25 pounds per 1,000 cubic feet of gas; with the carbon content taken as 24.66 per cent, 1.05 pounds of carbon per 1,000 cubic feet is given for this item. The checker-chamber refuse amounted to 4.8 pounds per 1,000 cubic feet and the carbon content averaged 81 per cent of carbon, giving 3.88 pounds of carbon per 1,000 cubic feet of gas. The tar produced amounted to 3.76 pounds per 1,000 cubic feet of gas. Its carbon content was 89 per cent, or 3.34 pounds per 1,000 cubic feet. The finished gas from analysis gave an equivalent of 22.78 pounds of carbon per 1,000 cubic feet. On the assumption that the deposit of carbon remaining in the set per 1,000 cubic feet of gas made is negligible, the difference between carbon input and these items of carbon output is the amount of carbon to be accounted for by the blast gases. The carbon items may be summarized as follows:

Summary of carbon balance

Carbon Input per 1,000 Cubic Feet of Finished Gas, Pounds

In generator fuel	32.17
In oil	22.36
Total	54.53

Carbon Output per 1,000 Cubic Feet of Finished Gas, Pounds

Generator refuse	1.05
Checker-chamber refuse	3.88
Tar	3.34
Finished gas	22.78
Total	31.05

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The difference, 23.48 pounds per 1,000 cubic feet of gas, represents carbon not accounted for. According to the analysis in Table 4, the blast gas at the stack contains the equivalent of about 4.25 pounds of carbon per 1,000 cubic feet of stack gas, and as 23.48 pounds of carbon are to be accounted for per 1,000 cubic feet of finished gas, the volume of stack gas per 1,000 cubic feet of finished gas is $\frac{23.48}{4.25}$, or 5.53 M. cubic feet when corrected to 60° F. and to a 30-inch barometer.

HYDROGEN BALANCE

In order to determine the amount of water vapor in the stack gas, a hydrogen balance of operation was worked out and the hydrogen equivalent of the water in the stack gases was determined by difference. Analyses of the generator fuel and the oil gave their ultimate hydrogen content, and the hydrogen equivalent of the moisture in the fuel and air and the hydrogen equivalent of the steam were taken as one-ninth the weight of the water. To determine the hydrogen in the outgoing products required more computation. The hydrogen in the make gas and in the stack gas was computed from the analyses, both as elementary hydrogen and hydrocarbons. The illuminants of the gas were assumed to average C_3H_6 in composition, this being the nearest equivalent to the heating value of the illuminants as determined by analyses and calorimeter tests.

As previously stated, the water in the make gas was determined by direct weighing and its hydrogen equivalent was readily computed. The hydrogen in the tar was determined by analysis. The following summarizes the hydrogen balance:

Hydrogen balance, pounds of hydrogen per 1,000 cubic feet of finished gas

Input	
Coal (dry), 42.5 pounds × 0.049	2.08
Oil, 26.7 pounds × 0.1296	3.46
Steam, 50.5 pounds × 1/9	5.61
Moisture in 4,100 cubic feet of air—	
Humidity, 50 per cent at 65° F., $\frac{4{,}100 \times .01346}{2 \times 9}$	.23
Water in generator fuel as charged, $\frac{3.5}{9}$ pounds	.39
Total	11.77
Output	
H_2 and equivalent in dry finished gas	4.69
Water as undecomposed steam in make gas, $\frac{38.6}{9}$	4.30
H_2 in tar, 3.76 pounds × 0.0553	.21
H_2 and equivalent in dry blast gas	.22
Water carried by stack gas, by difference	2.35
Total	11.77

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The water equivalent of the hydrogen in water carried by the stack gas is $9 \times 2.35 = 21.15$ pounds.

HEAT BALANCE OF OPERATION

The heat balance of operation can be worked out from the data given in the preceding tables and computations. Tables 5 and 6 show the balance obtained, calculated per 1,000 cubic feet of finished gas.

TABLE 5.—*Heat input per 1,000 cubic feet of finished gas during test*

	B.t.u.	Per cent of input
1A Heat of combustion of generator fuel, 46 pounds×12,465 (B. t. u. per pound as charged)	573,400	50.0
2A Sensible heat of air blast, 4,100 cubic feet or 314 pounds × .237 (specific heat) × (5° F.)	372	----
3A Steam to generators 50.5 pounds (7.3 pounds pressure and 34° F. superheat) × [(1158—201) +.475 (specific heat) × 34]	49,144	4.3
4A Heat of combustion of oil to sets, 3.72 gallons or 26.7 pounds×19,575 (B. t. u. per pound)	522,650	45.2
5A Heat carried by water vapor in air blast 2.07 pounds at 65° F	negligible	----
6A Sensible heat of coal	negligible	----
7A Sensible heat of oil, 26.7 pounds ×0.4 (specific heat) ×33° F	352	----
8A Heat in boiler-feed water, 92.7 pounds × (122–60)° F. above 60° F	5,744	0.5
Total	1,151,662	100.0

TABLE 6.—*Heat output per 1,000 cubic feet of finished gas during test*

	B.t.u.	Per cent of heat input
1B. Heating value of finished gas	561,000	49.0
2B. Heat in undecomposed steam, 38.6 pounds at 726° F. or 38.6×[(212—60) +970.4+ (.462×514)]	52,290	4.6
3B. Sensible heat in illuminating gas 23.8 (specific heat per 1,000 cubic feet) ×666 (°F. rise)[a]	15,704	1.4
4B. Sensible heat in stack gas, 5.53 1,000 cubic feet×20.44 (specific heat per 1,000 cubic feet) ×896 (°F. rise)[a]	91,277	7.9
5B. Heat of combustion of unburned stack gas, 5,530×23.2 (B. t. u. per cubic foot)	128,400	11.1
6B. Water vapor in stack gas, 21.15 pounds×[.51 (specific heat) × (956—212) +970.4+ (212—60)]	31,750	2.7
7B. Blown-over fuel, heating value, 4.8 pounds×11,497 (B. t. u. per pound)	55,100	4.8
8B. Unburned fuel from generator, 4.25 pounds×3.72 (B. t. u. per pound)	13,480	1.2
9B. Sensible heat in rejected fuel and ash, 9.05 pounds×0.2 (specific heat) ×1,040 (°F. rise)	1,882	0.2

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	B.t.u.	Per cent of heat input
10B. Steam generated in waste-heat boilers, 91.3 pounds× 1,134.7 (B. t. u.) +1.39 pounds×227 (water blown down)[a]	104,000	9.1
11B. Heating value of tar, 3.76×16,750	62,980	5.4
12B. Sensible and latent heat of tar, 3.76×(150+.65×664)	2,184	0.2
13B. Radiation and convection	11,770	1.0
	1,131,817	98.6

[a] Incomplete cleaning of interior of tubes of fire-tube waste-heat boilers affected these items materially. See text.

The heat balance given above leaves an unaccounted-for heat loss of 1.4 per cent, which is very small for a test of this kind, and probably as low as can be expected.

CONDITIONS REVEALED BY HEAT BALANCE

Inspection of the heat-output items at once brings out the fact that some of the losses are unduly large and suggests measures to be taken for the reduction of these losses.

UNDECOMPOSED STEAM

The first condition that one notices when inspecting the balance is the large excess of undecomposed steam passing the generator fuel-bed. For the production of 1,000 cubic feet of carbureted water gas, or perhaps 800 cubic feet of uncarbureted water gas of the average composition shown by analysis, approximately 18.5 pounds of steam would be required, if it is assumed that approximately 8 per cent of the blue gas was in fact coal gas from the distillation of coal in the generator.

This leaves 32 pounds of undecomposed steam if the amount metered to the sets—50.5 pounds per 1,000 cubic feet of gas—was correct. Direct determination of undecomposed steam showed 38.6 pounds per 1,000 cubic feet of finished gas. It is quite probable that there was some error in the metering of the steam as well as in the determination of undecomposed steam. There was probably about 35 pounds of undecomposed steam or approximately twice the excess that would ordinarily be expected with good coke or anthracite operation, because even with good operation it is seldom practicable to decompose more than half the steam supplied to the generator.

An excess of steam is necessary to make the clinker easy to handle, and a certain amount almost invariably leaks past the hot valves. The excess steam used during this test was somewhat greater than has been used with bituminous coal in smaller sets, because holes were invariably present in the fuel bed, even though precautions were taken to distribute the fuel on the surface of the fire. One result of these holes through the fuel bed, as noted before, was to cause con-

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siderable secondary combustion in the top of the generator; unless a large excess of steam was used to cool the top, the coaling sleeves, lids, and upper hot valves were soon overheated. On one occasion when the steam was reduced for trial, the generator lids soon became red hot. Experiments are continually being made to find an operating method that will eliminate channeling of the fuel bed, but thus far they have not been entirely successful.

INCOMPLETE ABSORPTION OF HEAT FROM GASES

Another condition affecting several of the heat-output items is the rather incomplete absorption of heat by the waste-heat boilers, which results in the gases leaving at temperatures much too high and thereby carrying with them an excessive amount of sensible heat. This condition may result from two things: 1, Lack of enough heat-absorbing surface in the boilers; and 2, unfavorable conditions of the absorbing surface. In the test described herein the second condition seemed to be the more important.

Much trouble has always been experienced when hot illuminating and blast gases alternately are passed through the same boiler. The illuminating gas at this stage is loaded with tar vapors from the cracking of the carbureting oil and as the temperature of the boiler tubes is considerably lower than that of the gases passing through, some of the heavier tar vapors invariably condense on the interior walls of the tubes. The blast gases bake this condensed tar on the tubes into a hard carbonaceous layer which continually increases in thickness. It is of course a much poorer conductor of heat than the steel boiler tubes themselves; consequently, as the layer thickens the amount of heat that can be transmitted per unit of time decreases continually and the gases leave the boiler at increasing temperatures. The tarry layer is so dense and adherent that it is removed only by the use of steam or air driven turbine tube-cleaners, and then with difficulty.

At the time of the test, this cleaning had to be repeated about every two weeks to keep the temperatures of the outgoing gas within reasonable bounds. It is usually said that with good operation the temperature of the stack gases should not exceed 700° F. and that of the outgoing illuminating gases 600° F. During the heat-balance test, however, the stack gases averaged 956° F. and the illuminating gases 726° F. It was evident therefore that the tubes were not being thoroughly cleaned or that the volume of the gases greatly exceeded the capacity of the boilers to handle it. Although there are indications that the volume of stack gases due to the combustion of gases from bituminous coal was somewhat in excess of boiler capacity, this was not true for illuminating gases. Upon further examination

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it was found that the turbine cleaner in use was designed for 3½-inch boiler tubes, whereas the internal diameter of the tubes of the waste-heat boilers was 4 inches. A deposit averaging about one-quarter inch thick was therefore present on the tubes throughout the test. The effect of this layer on evaporation, as evidenced by later performance, will be noted on page 33.

HEAT OF COMBUSTION OF UNBURNED STACK GAS

Another and important source of heat loss is evidenced in item 5B. The blast gas passing from the boilers up the stack had an average heating value of 23.2 B. t. u. per cubic foot. It is interesting to note that the analysis of the stack gases in Table 3 shows that oxygen, carbon, monoxide, and methane are present at the same time. Had they been present together only occasionally, their presence might have been attributed to errors in analysis, but the fact that they were present frequently indicates that the analyses are correct and that their simultaneous presence was probably due to the rapid passage of blast gas and air through the boilers without thorough mixing until after the temperature was too low to insure complete combustion.

Very dense smoke came from the stacks at times, and analyses often indicated lack of enough air. The admission of secondary and tertiary air for combustion was governed by the automatic mechanism that performed all the valve changes and did not permit individual regulation or regulation according to the particular air requirements at any instant. Though the valves admitting air were open, they were opened to the same degree all the time, so that sometimes there was an excess of air and sometimes not enough. Hand regulation of the tertiary air supply, subsequently tried, gave greatly increased efficiencies, as will be discussed on page 33.

BLOWN-OVER FUEL

Item 7B accounts for nearly 5 per cent of the heat loss and represents an almost unmitigated evil—the blowing over of generator fuel into the oil-fixing chambers. Though this blown-over fuel has some value as boiler fuel—it has a heating value of 11,497 B. t. u.—its presence in the checker chambers represents poor operating conditions. The carrying over of this fuel seems to be intimately connected with channeling of the fuel bed which, as previously stated, is a source of nearly all the operating troubles that have been experienced at this plant. Since the completion of the test herein described, it has been found that variations in blast pressure under the fires, rather than high blast pressure, seem to be largely responsible for carrying over the fuel. Regulators for maintaining a uniform

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pressure in the blast main have since been installed and have decreased the amount of blown-over fuel by more than 50 per cent.

The items of heat output enumerated above represent those heat losses of the process that are more or less subject to reduction when operation improves. The other items are for the most part small and of such a nature that they can not be reduced much. The heat balance fulfills its main purpose of pointing out the avenues of heat loss and has brought about marked improvement in operation.

POSSIBILITIES OF FURTHER HEAT CONSERVATION

Inspection of the items of heat loss (p. 28) shows that items 4B and 5B offer perhaps the most immediate opportunities for improvement; these are of such magnitude that the saving obtained by reducing them appreciably would be great. If the boiler tubes could be cleaned often enough to keep the stack temperature down to an average of 700° F. during the blow period, the resultant saving of heat would be measured by the heat-carrying capacity of the gas through a range of 196° F., since the average during the test was 896° F. If a specific heat of 20.44 B. t. u. per 1,000 cubic feet per degree rise in temperature is assumed, the heat saving per 1,000 cubic feet of stack gas would be $5.53 \times 20.44 \times 196 = 22{,}153$ B. t. u.

For item 5B, complete combustion of the stack gases would result in the liberation of 128,400 B. t. u. additional heat per 1,000 cubic feet of finished gas. Not all of this heat could be saved, for the combustion products would carry off a certain amount of it as sensible heat. The burning of the combustible gas in 5,530 cubic feet of stack gases would represent about 1,940 cubic feet of combustion products under standard conditions, which would total about 7,470 cubic feet. Of this approximately 265 cubic feet would be water vapor, leaving 1,675 cubic feet of dry stack gas in addition to that previously present. If a stack temperature of 700° F. be assumed, the heat loss in the dry stack gas would be about $(700-60) \times (1.675 \times 20.44) = 21{,}750$ B. t. u.

The water vapor previously in the stack gas and that formed by burning the remaining combustible gas in the stack gas would carry out of the boilers about $25.62\ [152+965.7+.51\ (700-212)] = 35{,}000$ B. t. u.

Deducting the sum of these items $(21{,}750+35{,}000=56{,}750)$ from 128,400 B. t. u. leaves 71,650 B. t. u., which added to the estimated saving in item 4B through lower stack temperature gives $71{,}650+22{,}153=93{,}803$ B. t. u.; this, in addition to the 104,000 B. t. u. previously absorbed by the waste-heat boilers per 1,000 cubic feet of finished gas, makes the heat absorption 197,803 B. t. u. or 189.5 per cent of the previous performance, equivalent to an evaporation of 191.5 pounds of water per 1,000 cubic feet of finished gas or the de-

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velopment of 1,118 boiler horsepower. This total would undoubtedly be beyond the capacity of the present single-pass boilers, but it shows the possibilities of steam generation with bituminous coal. In addition to these large items, reduction of stack temperatures would decrease the losses in items 2B, 3B, 6B, and 12B and possibly also in 13B (p. 28). The savings in these items, however, are relatively small.

SUBSEQUENT OPERATING RESULTS

The heat-balance test just described gave the operating company needed information on the avenues of heat loss and it immediately began eliminating these losses as rapidly as possible. Because of the nature of some of the heat losses, improvement has been gradual and experiments continue.

Elimination of the losses caused by the blowing over of fuel into the checker chambers was one of the first problems attacked. The installation of regulators for holding the blast main pressure constant resulted, as stated before, in marked diminution in the fuel blown over, reducing it to less than half of what it had been.

Discovery that the flue cleaner was too small resulted in the use of a cleaner of proper size and materially increased heat absorption by the boilers.

The most marked improvement in boiler operation was realized by carefully regulating the amount of tertiary air admitted to burn the blast gases in the boilers. By this means alone the evaporation per unit of finished gas made was increased nearly 50 per cent. When this report was written it was the sole duty of one man to observe the smoke issuing from the waste-heat boiler stacks and so to regulate the tertiary blasts to the sets operating that the density of the smoke indicates what experience has shown to be the most efficient combustion. It has been impractical to eliminate the smoke entirely because then the losses from excess air overbalance the advantages of complete combustion. Spot lights illuminate the stacks at night, enabling the operator to regulate the tertiary air supply quite as well as during the day.

Certain modifications of the operating cycle which are not required in the smaller gas sets operating with coal fuel without waste-heat boilers have been found advisable in the Joliet plant. Experience at Joliet has shown that the blow-run cycle, used to advantage in smaller sets, unduly reduces the heating value of the uncarbureted gas in large sets and necessitates the use of an excessive amount of oil. During the heat-balance test heretofore described, 3.72 gallons of oil was consumed in making 1,000 cubic feet of 561-B. t. u. gas. By eliminating the blow run, the oil can be de-

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creased materially. During September, 1922, the following operating results were obtained, the blow run being omitted:

Results at Joliet plant during September, 1922

Gas made	1,000 cubic feet	164,828
Generator fuel	pounds	6,668,400
Oil used	gallons	520,940
Generator fuel per 1,000 cubic feet, net	pounds	39.98
Oil per 1,000 cubic feet	gallons	3.17
Heating value of gas made	B. t. u.	543
Total machine hours		2,508
Number of runs		2,584
Make per machine hour	cubic feet	65,500
Make per run	do	6,350
Coke, recovered from checker chambers, etc	tons	142

The reader will note that although the consumption of oil decreased about 0.5 gallons per 1,000 cubic feet of gas made, the heating value of the gas decreased only 18 B. t. u. Simultaneously the gas make per machine hour declined from 80,800 cubic feet to 65,600 cubic feet or from about 48 per cent to about 39 per cent of the rated capacity. On the assumption that there is capacity to make enough gas at this lowered rate of production, the question to be decided is evidently whether the cost of operating a longer time or of using an additional set will offset the value of the oil saved. In the present instance, the management believes that the saving in oil cost overbalances any advantages obtained from the blow run.

In smaller sets, even a blow run of 30 seconds at ordinary blast pressures increased the oil consumption hardly more than 50 per cent of the increase shown in the present tests. The difference is doubtless partly accounted for by holes in the fire, which lower the quality of the blow-run gas, and partly by the larger volume of burned gases remaining in the set and the boiler at the close of the blow. Unless the secondary and tertiary air to the set are interrupted long enough before the stack valve is closed and the blow run begun, much burned or partly burned producer gas of very low heating value will pass into the relief holder.

In the results for September, 1922, just given, the generator fuel shows some improvement in spite of the elimination of the blow run, being practically 40 pounds per 1,000 cubic feet of gas net, whereas during the heat-balance test the generator fuel was 46 pounds gross. Deducting 10.4 per cent for blown-over fuel gives 41.2 pounds per 1,000 cubic feet net. Part of the improvement in performance was possibly due to the use during September of a West Virginia gas coal containing somewhat less volatile matter than the southern Illinois coal used during the greater part of the heat-balance test.

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ECONOMIC PHASES OF THE USE OF BITUMINOUS GENERATOR FUEL IN LARGE SETS

In spite of the lower rates of gas production obtained in large sets with bituminous coal, economic considerations sometimes favor its use, as in the Joliet plant at present. When the economic phases of the subject are discussed, the performance in one plant can not be taken as typical of all plants. The relative economies of two generator fuels, such as bituminous coal and coke, depend upon so many factors that no direct comparison can be made based on pounds of coal and gallons of oil used to make gas of a prescribed quality.

When processes are compared the capital charges are often neglected, but these charges may be just as important in determining the economic feasibility of a process as the costs of the physical commodities employed, and no cost comparison is complete unless it considers them.

One of the first considerations involved in a study of this kind is the volume of the gas output. In the present tests this may be taken as 6,000,000 cubic feet per 24 hours. The production capacity realized on 11.0-foot sets with coal fuel is approximately 40 to 50 per cent of the nominal rated capacity with coke, which is usually assumed to be 3,500,000 cubic feet of finished gas per set per 24 hours. Although this rate of make may be and sometimes is exceeded, it presupposes a good grade of coke, ample blast and steam, and other conditions that may not always be present. If it is assumed that about this rate of production can be maintained, it is probably safe to assume also that an installation of three sets using coke fuel would supply enough gas at all times to maintain the daily output of 6,000,000 cubic feet and give ample excess capacity to allow a safe margin for repairs, recheckering, and other ordinary happenings that might necessitate a partial shutdown of the plant.

On the other hand, with coal fuel, six sets each, producing 1,375,000 cubic feet of gas daily, would be necessary to give one spare set for emergencies. Five sets would make 6,877,000 cubic feet a day and the sixth could be down for repairs, recheckering, and so on. Thus while production per set with coal is assumed to be only 40 per cent of that with coke, it is possible, on account of the smaller unit of production with coal, to get along quite safely with double the generating capacity.

CAPITAL CHARGES

A plant of 6,000,000 cubic feet capacity, designed to use bituminous coal, would therefore represent an investment for three additional sets and their appurtenances. In the tests under discussion the equipment was very complete. Each set had an automatic control and a single-pass vertical waste-heat boiler.

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Prices of equipment fluctuate and depend somewhat upon location, conditions, and labor costs. The writer is informed that $60,000 represents in round numbers the cost of a single 11.0-foot set with a waste-heat boiler, automatic controls, and minor accessories. A plant using bituminous coal fuel would therefore cost $180,000 in excess of one using coke to produce 6,000,000 cubic feet of gas a day, with the margin of safety stated. A building to house the additional equipment would, of course, be necessary. Thirty thousand dollars would probably defray this expense, making $210,000 in all. It is believed that 10 per cent of the investment would cover interest, taxes, and cost of marketing securities and that 5 per cent would cover depreciation charges. Of course different rates would apply on equipment and building, but as the latter is a small part of the total investment the application of a 5 per cent depreciation charge to the whole investment would probably err on the side of safety.

The total capital charge would therefore be $31,500 a year or, for an annual output of 2,190,000,000 cubic feet of gas, would be 1.44 cents per 1,000 feet on the additional investment for using coal fuel. It is evident that on this scale of operation the capital charges per 1,000 feet of gas produced are likely to form a very small item in comparison with other factors, yet the additional investment is often one of the first objections mentioned in connection with the practicability of using coal. The writer admits that in congested localities where the cost of land is excessively high or under business conditions that make money well-nigh unobtainable, the problem might be quite different from that considered above. It would be very unwise to take the conditions at this plant as typical of those at all plants.

OPERATING COSTS

The operating expenses include the costs of labor and materials and depend not only on unit prices but also on efficiency of operation. Since the plant upon whose performance this estimate is based had never used coke for an extended period when making carbureted water gas, certain assumptions, based upon good operation in other plants, must be made for the use of coke. The coal-operation costs presented, however, are believed to represent fairly the average practice in the Joliet plant at the time of writing.

LABOR

As heretofore assumed, it would probably be necessary to operate five sets continuously with coal fuel or two sets with coke fuel, and hold one set in reserve. Under the efficiencies now obtainable with coal, it would be necessary to handle about one-third more

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fuel for the same make of gas. Moreover, additional labor would be necessary for operating three additional sets and for cleaning fires, checker-chamber bottoms, and boilers. Three more waste-heat boilers would have to be watched. On the other hand, some advantages offset these additions. Less labor would be required in the boiler room on account of the increased generation of steam by waste heat with coal fuel. Although fire cleans would probably be more numerous with five sets in use, past experience indicates they would probably be less arduous with coal than with coke. By the use of automatic controls one operator might be able to run the coke installation of two sets. With coal as fuel it is not believed that it would be practicable to dispense with any operators under existing conditions. There is little reason for any appreciable difference in the yard labor necessary. If certain coals were used, the purifying cost might be greater with coal than with coke, but when low-sulphur gas coal is used as generator fuel, as at Joliet, no difference in this cost is observed. At present the cost of operating labor in the plant using coal fuel amounts to 3.8 cents per 1,000 cubic feet of gas made. It is not believed that this item would be reduced by more than 0.8 per cent if coke were used.

OPERATING MATERIALS

The cost of operating materials is usually the most important factor in a problem of this kind, for upon it largely depends the answer. Certain standard items, such as purifying oxide, boiler compound, waste, lubricating oil, and water, are little affected by the generator fuel used. The same cost per 1,000 cubic feet of gas, 1.1 cents, is assumed. The cost of gas oil would be more important were it affected by the fuel used, but under prevailing conditions an oil consumption of 3.2 gallons to produce a 544-B. t. u. gas is believed to be about the same as with coke fuel. This item can therefore be neglected.

Generator fuel remains the most important item. The results obtained indicate that 40 pounds per 1,000 cubic feet of gas made is an average that can be maintained. In 1922 coal delivered to the sets cost $8.50 per short ton of 2,000 pounds. Evaporation in the coal-fired boiler plant is not as efficient as it should be with improved equipment. It averages about 6 pounds of water to a pound of boiler fuel, which costs $5.50 a ton. Coke is high at Joliet; the manager of the plant stated that coke did cost $15 a ton in 1922, though it was possible that this price could have been materially reduced on a long-time contract. It is not believed that with coke a generator-fuel figure much lower than 30 pounds per 1,000 cubic feet could be consistently maintained. On this basis the cost of generator

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fuel per 1,000 cubic feet of gas made would be 17 cents for coal and 22.5 cents for coke, a saving of 5.5 cents with coal.

Boiler fuel is another important item when bituminous coal is used. With coal fuel the waste-heat boilers evaporate 125 to 150 pounds of water for each 1,000 cubic feet of gas made. For the single-pass boilers used it is understood that the builders guarantee not more than 40 pounds evaporation per 1,000 cubic feet with coke fuel. A 50 per cent addition, making 60 pounds per 1,000 cubic feet, is allowed here for actual operation. At the plant in question, with excess steam used, as is necessary to prevent overheating of generator tops and hot valves, about 50 pounds of generator steam is used per 1,000 cubic feet of gas, making an excess of about 20 pounds per 1,000 cubic feet.

The total steam requirement of the water-gas plant is estimated to be 90 pounds per 1,000 cubic feet of gas to the holder, not including that used for transmission pumping and electric generation. With coke the requirement would be about 70 pounds. Therefore waste-heat boilers with coal fuel give an excess of 35 to 60 pounds per 1,000 cubic feet over manufacturing requirements and coke would give a deficit of 10 pounds, a credit in favor of coal, at the lower evaporation figure of 45 pounds, equivalent to about 7.50 pounds of boiler fuel per 1,000 cubic feet, worth 2.05 cents. Such an amount of excess steam could not be utilized in every plant, but at present all is required and more besides, for distribution pumping and the operation of electrical machinery. Partly coked fuel blown over to the checker chambers and recovered averages about 1.72 pounds per 1,000 cubic feet, has a heating value of about 11,750 B. t. u. per pound, and would be worth perhaps $4 per ton in the boiler room, corresponding to a credit of 0.34 cents per 1,000 cubic feet for coal operation.

MAINTENANCE COSTS

Maintenance charges for large sets using bituminous coal as fuel are undoubtedly larger under present operating conditions than for the same sets using coke. This increase is not due to the effect of clinkers on the generator linings, since clinker from bituminous coal gives less trouble than that from many cokes. The action on the upper part of the generator and the hot valves is more severe because of holes through the fire, and the deposition of fuel in the checkerwork makes recheckering necessary more often than with coke fuel. These troubles have been largely overcome, as compared with conditions when the use of coal began, and there is hope that eventually they may be eliminated. At the time of writing, however, practice shows that maintenance charges for coal fuel differ dis-

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tinctly from those for coke. A typical month's operation of the plant at Joliet showed a maintenance labor charge of 0.8 cent per 1,000 cubic feet and a maintenance material charge of 1.3 cents per 1,000 cubic feet. If five sets were using coal or two sets using coke to make the required amount of gas, the maintenance costs with coal would probably be much more than in proportion to the number of sets in operation. It is estimated that under the conditions prevailing in Joliet the maintenance labor would be about 0.3 cent and the maintenance supplies 0.4 cent with coke fuel, a total difference in favor of coke of 1.4 cents per 1,000 cubic feet.

SUMMARY OF COST COMPARISON

The items of comparison heretofore enumerated are summarized below. Quantities that favor coke fuel are indicated by minus signs:

Differences in items of cost of producing gas with coke and with bituminous coal

	Cents per 1,000 cubic feet of gas made
Capital charges (interest, depreciation, taxes, marketing securities)	—1.44
Operating labor (including superintendence)	—0.80
Operating supplies (general)	0.00
Gas oil	0.00
Generator fuel	5.50
Boiler fuel	2.05
Credit for blown-over fuel	.34
Maintenance (labor and materials)	—1.40
Difference in favor of coal	4.25

Making absolute comparison in a case of this kind is so difficult that small errors are likely to enter. It is believed, however, that the comparison given above is conservative. In a comparison which the writer made recently in cooperation with the manager of the Joilet plant there was a difference of 6.3 cents per 1,000 cubic feet of gas. In that comparison, however, 32 pounds of coke per 1,000 cubic feet of gas was assumed, evaporation in the waste-heat boiler with coke was taken as 40 pounds per 1,000 feet, and only five sets were assumed to be necessary when coal was used. A smaller difference in operating labor, also, was allowed.

The difference in price of coal and coke is, of course, the main determining factor. As the prices of the two fuels change, the relative production cost will also change. The accompanying chart, Figure 4, is plotted to show that price of coal which would balance any given price of coke, all the other items of cost remaining the same as stated herein.

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Disposal of the excess steam generated by waste-heat boilers with coal as fuel is another important item. If this steam is in demand for transmission pumping, electric generation, or other purposes, a very distinct saving in boiler fuel and in boiler-house labor is effected by it. If there is no demand except for water-gas manufacture and part of the steam generated has to be wasted, the item would become less important.

SUMMARY OF CONCLUSIONS

1. The use of bituminous coal as generator fuel in very large water-gas sets, as, for example, the standard 11.0-foot set, is not as

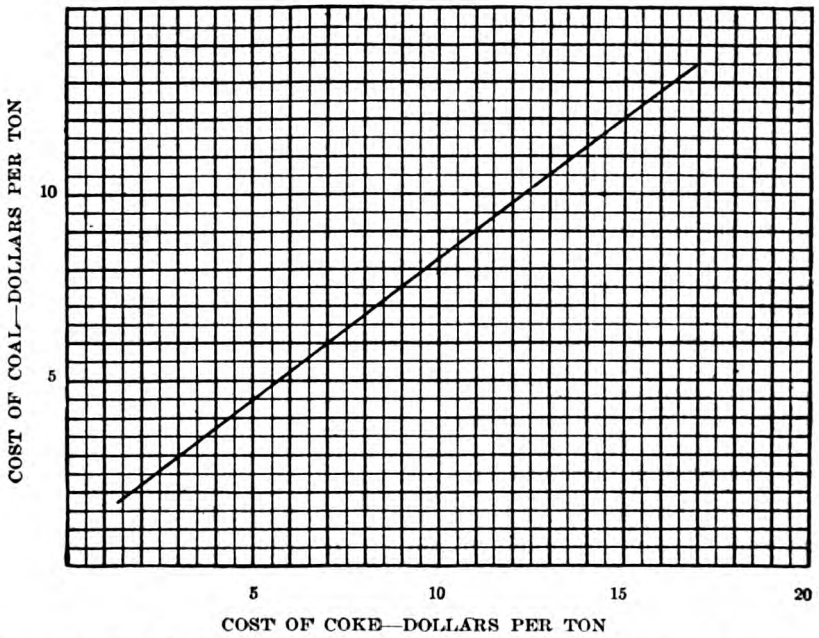

FIGURE 4.—Chart for determining costs of coal and coke giving same gas-production costs

successful with regard to capacity and operating efficiencies as in sets of smaller size.

2. In the very large sets the use of the blow-run cycle employed successfully in small sets decidedly increases the quantity of oil required to make a gas of given quality. In the plant under study at Joliet, Ill., the omission of the blow run reduced the rate of gas production by 20 per cent, but saved 0.5 gallon of oil per 1,000 cubic feet of finished gas.

3. With the blow run omitted, the production capacity was about 40 per cent of the nominal rated capacity of the water-gas sets when they used first-class coke as fuel.

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4. A waste-heat boiler is a successful adjunct to a larger water-gas set, especially when coal fuel is used. An evaporation of about 125 to 150 pounds of water per 1,000 cubic feet of finished gas made has been realized consistently when blast and make gases are passed through the boilers. An evaporation of 83 pounds per 1,000 cubic feet was obtained when blast gases only were used.

5. A heat balance of operation of three sets with three waste-heat boilers showed that 49 per cent of the heat input was in the heating value of the finished gas and 9.1 per cent in evaporation by the waste-heat boiler. These results have since been improved to about 53.7 per cent of the heat input in the finished gas and 14 per cent in the waste-heat boiler evaporation.

6. The formation of holes (channeling) through the generator fire even with moderate blast pressures is the outstanding difficulty in using bituminous coal in large generator sets. It is believed that by attention to the sizing of the coal and by care in spreading the charge this difficulty can be greatly reduced. Regulation to maintain a uniform blast pressure greatly reduces the blowing over of fuel into the checker chambers—a condition attributed chiefly to holes through the fire.

7. The spacing of the checker-chamber brick seems to be an important consideration when bituminous coal is used for large sets. The most successful arrangement that had been tried when this paper was written was the use of No. 3 arch brick spaced 3½ inches in straight flues in the carburetors and 9-inch straight bricks spaced 6 inches and staggered in the superheater. This arrangement permits a larger part of the blown-over fuel to sift through to the checker-chamber bottoms, where it can be readily removed through a quick-opening door placed on the rear side of the superheater in line with the tunnel between the carburetor and the superheater. The dust collectors should also be emptied at regular and rather short intervals. The brickless carburetor using high-pressure oil sprays is an innovation soon to be tried which promises much advantage with bituminous coal as fuel.

8. The economic success of operating with bituminous generator-fuel in large sets equipped with waste-heat boilers depends upon the price differential between coke and coal and the extent to which the steam generated in excess of requirements of generators and accessory equipment can be utilized. This can be estimated for any particular plant, but no general conclusions applying to all plants can be made.

9. The use of coal and coke mixtures in 11.5-foot sets has not been tried, as far as the writer is aware. From experiments in smaller sets, it appears likely that production capacity could be materially increased by using 20 to 25 per cent of coke. It also seems likely

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that such a mixture would reduce the excess steam now used when the fuel is coal alone, diminish the tendency for holes to form in the generator fire, decrease the percentage of blown-over fuel, decrease labor and maintenance charges, and at the same time give much of the economic advantage due to the lower cost of the coal fuel in the mixture. At the plant discussed in this paper, fuel-handling conditions seem to make experiments with mixtures impracticable at present.

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PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION

BULLETIN 203. Central District bituminous coal as water-gas generator fuel, by W. W. Odell and W. A. Dunkley. 1923. 89 pp., 10 figs.

TECHNICAL PAPER 9. The status of the gas producer and of the internal-combustion engine in the utilization of fuels, by R. H. Fernald. 1912. 42 pp., 6 figs.

TECHNICAL PAPER 246. Water-gas apparatus and the use of Central District coal as generator fuel, by W. W. Odell. 1921. 28 pp., 1 pl., 2 figs.

TECHNICAL PAPER 267. Stenches for detecting leakage of blue water gas and natural gas, by S. H. Katz and V. C. Allison. 1920. 22 pp., 2 figs.

TECHNICAL PAPER 274. Efficiencies in the use of bituminous coking coal as water-gas generator fuel, by W. W. Odell. 1923. 39 pp., 1 pl., 9 figs.

TECHNICAL PAPER 284. Coke and coal mixtures as water-gas generator fuel, by W. W. Odell. 1922. 32 pp., 4 pls., 2 figs.

TECHNICAL PAPER 304. Water-gas tar emulsions, by W. W. Odell. 1923. 51 pp., 6 figs.

PUBLICATIONS THAT MAY BE OBTAINED ONLY FROM THE SUPERINTENDENT OF DOCUMENTS

BULLETIN 6. Coals available for the manufacture of illuminating gas, by A. H. White and Perry Barker, compiled and revised by H. M. Wilson. 1911. 77 pp., 4 pls., 12 figs. 15 cents.

BULLETIN 7. Essential factors in the formation of producer gas, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1911. 58 pp., 1 pl., 16 figs. 10 cents.

BULLETIN 13. Résumé of producer-gas investigations. October 1, 1904 to June 30, 1910, by R. H. Fernald and C. D. Smith. 1911. 393 pp., 12 pls., 250 figs. 65 cents.

BULLETIN 55. The commercial trend of the producer-gas power plant, by R. H. Fernald. 1913. 93 pp., 1 pl., 4 figs. 20 cents.

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BULLETIN 109. Operating details of gas producers, by R. H. Fernald. 1916. 74 pp. 10 cents.

TECHNICAL PAPER 54. Errors in gas analysis due to the assumption that the molecular volume of all gases are alike, by G. A. Burrell and F. M. Seibert, 1913. 16 pp., 1 fig. 5 cents.

TECHNICAL PAPER 120. A bibliography of the chemistry of gas manufacture, by W. F. Rittman and M. C. Whittaker, compiled and arranged by M. S. Howard. 1915. 30 pp. 5 cents.

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